This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

Usage guidelines

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

+ *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.

+ *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.

+ *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.

+ *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

About Google Book Search

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at `http://books.google.com/`

QE
86
.G7
D38
1901

17 Dec 15

HARVARD UNIVERSITY

GEOLOGICAL SCIENCES
LIBRARY

Museum of Comparative Zoology.

May 29, 1901.

Transferred to
CABOT SCIENCE LIBRARY
June 2005

MAY 29 1901
14,964

Bulletin of the Museum of Comparative Zoölogy
AT HARVARD COLLEGE.
VOL. XXXVIII.

GEOLOGICAL SERIES, Vol. V. No. 4.

AN EXCURSION TO THE GRAND CANYON OF THE COLORADO.

BY W. M. DAVIS.

WITH TWO PLATES.

CAMBRIDGE, MASS., U.S.A.:
PRINTED FOR THE MUSEUM.
MAY, 1901.

QE
86
.G7
D38
1901

GEOLOGICAL SCIENCES
LIBRARY

FEB 2 1986

HARVARD UNIVERSITY

MAY 29 1901

No. 4.—*An Excursion to the Grand Canyon of the Colorado.*

By W. M. Davis.

TABLE OF CONTENTS.

PAGE
Introduction 108
  Itinerary 110
  Summary of Previous Work . 110
    Newberry 111
    Powell 112
    Dutton 113
  The Rock Series 115
  Local Names, Maps, etc. . . . 115
The Great Denudation 118
  Two Cycles of Denudation . . 118
  The Mature Valleys of the Kaibab and Coconino Plateaus . 120
  The Landslides of Vermilion and Echo Cliffs 121
  The Migration of Certain Divides 126
    Divide near Pipe Spring . . 126
    Relation of the Pipe Spring Divide to the Pipe Spring Fault. 128
    The Cedar Ridge Divide under Echo Cliffs 129
    Migrating Divides in Arid Regions 130
  The Permian Scarps under the Shinarump Cliffs 132
    The Development of Talus . 133
    Perched Boulders 134
    Spurs and Ravines 134
  The Stripped Plateaus 136
Dates of Displacements 139
  The Eastern Flexures 139
    The Earliest Flexures . . . 139
    The Kaibab and the Echo (Paria) Flexures 140
    The Crags of Echo Cliffs . . 141
  The Western Faults 142
    The West Kaibab Faults . . 142
    The Toroweap Fault 142
    The Sevier Fault Southwest of Pipe Spring 143
    Topographic Effects of Faulting obliterated or reversed by Erosion 145
    The Hurricane Fault 146
    The Grand Wash Fault . . . 147
  The Western Monoclinal Flexures 148
  The Displacements of the High Plateaus 150
Origin of the Drainage System . 151
  General Explanation by Antecedence 151
  Replacement of Antecedence by Other Explanations . . . 152
    The Smaller Streams of the Grand Canyon District . . 153
    The Streams of the San Rafael Swell 154
    The Summit Valleys of the Kaibab 155
  The Origin of the Colorado in the Grand Canyon District . 158
    The Geological History of the Region 159
    The Effect of the Flexures . 160
    The Effect of the Faults . . . 161
    The Bends of the Grand Canyon 164
    Speculative Character of the Preçeding Sections . . . 166
The Erosion of the Grand Canyon . 167
  The Canyon Cycle 167
    Comparison of Glen and Marble Canyons 167

PAGE
Stage of Development of the Canyon 168
Rapids in the Canyon . . . 168
Junction of Trunk and Branch Streams 169
The Geological Section in the Canyon Wall 171
The Two Unconformities . . 173
Correlation of Water Streams and Waste Streams . . . 176
Cirques, Cusps, and Niches . 178
The Esplanade 180
Two Theories of the Esplanade 181
Comparison of the Kaibab and the Kanab Sections . . . 181
Eastward Fading of the Esplanade 182
Relation of the Inner and Outer Canyons 183
Relation of the Esplanade to the Toroweap Fault . . . 184
Conclusion as to the Origin of the Esplanade 185
Hints for a Visit to the Canyon. 186
Former Climates of the Grand Canyon District 187
Diverse Opinions of Early Observers 187
Moist Miocene and Arid Pliocene Climates 188
The Toroweap 189
The Pluvial Equivalent of the Glacial Period 192
Volcanic Phenomena 192
Summary 195
Bibliography 197
Explanation of Plates 201

Introduction.

In June, 1900, it became possible for me to visit the district of the Grand Canyon of the Colorado, and to see upon the ground the wonderful features of a region that had long been familiar from the reports of our governmental surveys. Our party consisted of Prof. R. E. Dodge of Teachers' College, Columbia University, Prof. H. E. Gregory of Yale University, Mr. R. L. Barrett of Chicago, Mr. Richard Wetherill of Pueblo Bonito, N. M., Dr. Tempest Anderson of York, England, and the writer. We reached Flagstaff, Arizona, by the Santa Fe Western Railroad on June 3, spent twenty-three days travelling irregularly across country, and went out from Milford, Utah, to Salt Lake City by a branch of the Oregon Short Line on June 26. Our itinerary is shown on the accompanying outline map, Figure 1, with dates of camps, and in the list of camps given below. We travelled partly in wagon, partly on horseback, and averaged about twenty-five miles a day. The clouds of thunder showers were frequently seen in the distance, but we had rain only twice; first a few drops in the canyon, June 7, and next a brisk shower near the Little Colorado crossing on the morning of June 10; the centre of this shower passed north of us, and the muddy streams from its short-lived down-pour met us as we were ascending a dry arroyo, or "wady." Many days were almost cloudless and oppressively hot over noon. The nights were cool, with the exception of one that we spent near the bottom of the canyon, which was unpleasantly warm. A brief report upon our trip has already been published in the "American Journal of Science," for October, 1900.

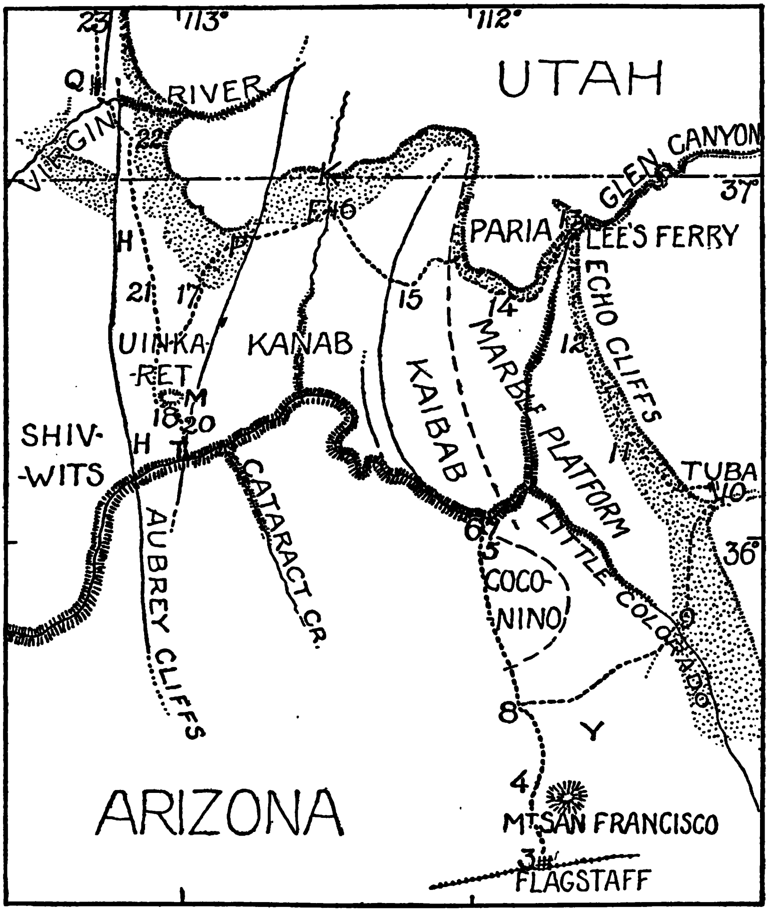


FIGURE 1.

Route-map of Grand canyon district. The dotted belt represents the weak lower Triassic and Permian strata separating the mesozoic area on the northeast from the palæozoic area on the southwest. The several blocked plateaus are separated by faults (continuous lines) or flexures (broken lines). The route followed is marked by a fine broken line, with numbers to indicate dates of camps in May, 1900. F, Fredonia; H, H, Hurricane ledge and fault; K, Kanab; M, Mt. Trumbull; P, Pipe spring; Q, Toquerville; T, Toroweap valley; Y, recent lava mesa. Outline taken from Dutton's Atlas.

ITINERARY. — June 4th, 1900, Flagstaff northward to Stokes spring, at northwest base of San Francisco mountain; 5th, northward to the Coconino forest, within four miles of Hance's on the canyon rim; 6th, descended from Cameron and Berry's Hotel by Grand View trail into canyon and spent the night at the level of the lower Tonto shales; 7th, returned to Cameron and Berry's; 8th, southward to Hull's spring on road to Flagstaff; 9th, northeastward to Little Colorado river at crossing of road from Flagstaff to Tuba; 10th, northward to Tuba; 11th, northward along base of Echo cliffs to Cottonwood tanks; 12th, still northward along Echo cliffs to Tanner's tanks; 13th, still northward along Echo cliffs, crossing the Colorado river at Lee's Ferry; 14th, southwest to Jacob's pools under the Vermilion cliffs of the Paria plateau; 15th, west to Jacob's lake on the Kaibab plateau; 16th, northwest to Fredonia; 17th, westward to Pipe spring and southwestward to Yellowstone spring near Antelope valley; 18th, southwestward to Trumbull spring at southern base of Mt. Trumbull;[1] 19th, ascended Mt. Trumbull, then southward to Oak spring; 20th, southward to Vulcan's throne in the Toroweap, and back to Oak spring; 21st, northward to Clay holes; 22nd, northward to Gould's (Workman's) spring; 23rd, northward past Toquerville to Kelsey's ranch; 24th, northward past Cedar City to Rush lake; 25th, northwest to Minersville; 26th, northwest to Milford; night train to Salt Lake City.

SUMMARY OF PREVIOUS WORK. — An account of new observations made in such a district as that of the Grand Canyon of the Colorado, already well studied by the explorers of our western surveys, naturally lays more emphasis on novel interpretations of former observations or on subordinate matters newly observed, than on the great structural features of the region or on the principal events of its history. But whatever of novelty is now to be gleaned in that marvellous region must rest so immediately on the work that has been already done there that I wish at the outset to express the great indebtedness that all of our party felt to the pioneer work of Newberry, Powell, Gilbert, Dutton, and Holmes, whose labors have transformed a desert wilderness into classic ground for the geologist, and whose reports are quoted whenever it is desired to illustrate all that is marvellous in the way of displacement and denudation. The topographical maps prepared by Bodfish and Renshawe in 1879 are also of great service to the traveller. The main conclusions of the earlier explorers are not to be disputed. The great unconformities at the base of the plateau series, the enormous volume of nearly horizontal and conformable strata from lower Palæozoic to Tertiary, the division of the region into great blocks by displacements, either faults or flexures, trending about north and south, the great denudation by which the plateaus bordering the canyon have been stripped of thousands of feet of strata, the sharp erosion by which the canyon has been incised in the plateaus, and the superb development of volcanic phenomena, — all these great features are standard examples for citation. There are, however, certain subordinate conclusions announced in the earlier reports which seem open to question, and it is chiefly to a consideration of these debatable points that the present essay is devoted.

---

[1] Trumbull spring is on the slope of the mountain several hundred feet above its base: at the time of our visit it gave very little water. The place is not to be recommended as a camping ground. Oak spring, four miles further south, is much better.

The following brief summary of certain aspects of the work of three earlier observers may be of service to the reader.

Newberry, geologist of the Ives expedition to the Colorado river of the west in 1857–58, ascended the Grand Wash cliffs to the plateaus from the deserts among the Basin ranges on the south of the river, descended northward into the Grand canyon near its western end by the side canyon of Diamond creek, and, ascending again, traversed the southern plateaus past San Francisco mountain from west to east. He recognized the fundamental crystalline rocks beneath their heavy unconformable cover of palæozoic strata (pp. 54–58); he perceived the importance and efficacy of ordinary erosive processes not only in the excavation of the narrow canyons beneath the plateaus by the larger and smaller streams (pp. 45, 46), but also in the broad recession of the cliffs upon the plateau (pp. 45, 62), indeed he regarded the opening of the broad upland valleys on the plateaus, such as that of the Little Colorado, as "a much grander monument of the power of aqueous action than even the stupendous cañon of the Colorado" (p. 86). He noted a "slight arching of the strata" in passing from what we may now call the southern Shivwits to the southern Uinkaret plateau (p. 58), and a "curve of the underlying rock" on descending from the Coconino plateau (south of the Kaibab) to the platform of the Little Colorado valley (p. 61); but he denied the occurrence of other displacements, not only in the canyons but also along the north-south escarpments, saying that "the strata of the table-lands are as entirely unbroken as when first deposited" (p. 46); and this is not unreasonable when it is remembered that his route led him across the southern plateaus where the great displacements weaken and disappear as they come down from the north. He did not demand two periods of erosion for the sculpture of the plateaus and the narrow canyon; difference of resistance in the upper and lower strata seemed to him to account for these contrasts in the amount of destructive work (p. 62), but he inferred a more active erosion in former times than at present; "everything indicates that the table-lands were formerly much better watered than they now are" (p. 47, also pp. 62, 76).

Powell in his adventurous expedition down the canyon (1869) and in his journey over the northern plateaus (1870), discovered the double unconformity in the Kaibab section of the Grand canyon (*a*, pp. 212, 213), gave many new details concerning the rock series, and emphasized the production of the canyons by erosion in his announcement of the "antecedent" origin of certain rivers (p. 163). He presented a clear account of the great displacements by faults and flexures which divide the Grand canyon district into huge "blocks," trending north and south (*a*, pp. 185–190, Figure 73), as well as of the great cliffs of erosion or retreating escarpments, north of the canyon, facing south and trending irregularly east and west (*a*, pp. 190, 191, Figure 74); "the cliffs of erosion are very irregular in direction, but somewhat constant in vertical outline; and the cliffs of displacement are somewhat regular in direction, but very inconstant in vertical outline" (*a*, p. 191). Powell does not seem to have felt the necessity of supposing an uplift of the region between the great denudation of the uplands and the incision of the narrow canyons (pp. 206, 213), but he states that "the carving of the cañons . . . is insignificant when compared with the denudation of the whole area, as evidenced in the cliffs of erosion" (*a*, p. 208). The date of the displacements is not very sharply defined; when the great denudation began "there were no faults and no benches" (*a*, p. 200). The first displacements occurred after the erosion of valleys had been begun, the displacements were long continued, and must have been slower than the erosion of valleys by the principal streams, for the displacements did not modify the stream courses (*a*, p. 201). "Though the entire region has been folded and faulted on a grand scale, these displacements have never determined the course of the streams. . . . All the facts concerning the relation of the water-ways of this region to the mountains, hills, cañons, and cliffs lead to the inevitable conclusion that the system of drainage was determined antecedent to the faulting and folding" (*a*, p. 198). The recession of cliffs is greater in the plateau blocks of greater uplift than in those of less uplift (*a*, p. 191). Volcanic action began with the period of displacement and continued till after the Grand canyon had been eroded (*a*, pp. 201, 94, 131); a close relation is inferred between the lines of fracture and the location of the volcanic vents (*a*, pp. 6, 94, 196). An arid climate is thought to have long prevailed, for otherwise the cliffs and canyons could not have maintained their sharp forms (*a*, pp. 204, 209, 211). Some additional details concerning the stratigraphy of the plateau series are presented in Powell's "Geology of the Uinta Mountains" (*b*, pp. 43, 54, 62, 70).

Dutton first presented his conclusions in a report on the "Geology of the High Plateaus of Utah" (1880); they were afterwards elaborated in his "Tertiary History of the Grand Canyon District" (1882). Reference is here made chiefly to those points which carry the study of the region beyond the stage reached by Dutton's predecessors. Several periods of uplift and displacement are given geological dates, but in the absence of the later Tertiary deposits, such terms as Miocene and Pliocene are used only in a general way (*c*, p. 192). One of the oldest displacements is the Waterpocket flexure, involving all strata up to and including the Cretaceous; it is crossed by the Colorado in Glen canyon, and is unconformably buried in the northwest by the horizontal Eocene strata of Thousand lake mountain, one of the high plateaus (*a*, pp. 44, 288, *c*, 215). The whole region began to rise in the early Tertiary (*a*, pp. 14, *c*, 219), and several broad gentle swells were at the same time locally elevated above their surroundings; one of these was the San Rafael swell (Miocene) north of the Henry mountains, and another of much greater size was the Grand canyon district (late Eocene, *a*, p. 19). Faults and flexures in the Grand canyon district were of later date. The whole uplifted region was greatly eroded in Miocene time, and more slowly in Pliocene time (*a*, pp. 18–21). The first chapter of erosion, frequently named "the great denudation" and placed in Miocene time, witnessed the removal of strata having an average thickness of six thousand feet from a broad area in the Grand canyon district, reducing the surface to moderate relief, "a very flat expanse" (*c*, p. 77, also pp. 119, 224). On such a surface, the volcanic eruptions which had begun at an earlier period poured forth great flows of lava; eruptions continued still later, the vents being generally independent of fault lines, even though new vents were made after the time of faulting (*c*, pp. 105, 107). The high plateaus of Utah are residual table-lands capped by Tertiary strata and lavas, remnants of the great denudation that stripped the lower plateaus on the south and east (*a*, p. 22). It was after the great Miocene denudation that the Kaibab and the Echo cliffs monoclines began to have a separate existence (*a*, p. 42, *c*, pp. 192, 205), and with these local uplifts there was also a wide-spread and sudden uplifting of the whole district in virtue of which the deep and narrow canyons of to-day have been cut (*a*, pp. 38, 45, *c*, pp. 100, 191); it is by this uplift of late date that the high plateaus of Utah have reached their great altitude (*a*, p. 23). The system of north and south faults, extending from the Grand canyon northward into the high plateaus, was closely associated with the Pliocene uplift of the region, although some of them may have begun earlier and continued later, even as late as the glacial period (*a*, pp. 27, 28, 35, *c*, pp. 94, 116, 187, 191, 226). It was during a pause in the Pliocene uplift that the esplanade of the "outer gorge" in the Kanab and Uinkaret plateaus was opened (*c*, pp. 121, 226, 227), while the inner gorge of the Grand canyon in these plateaus has been eroded since the later faulting took place (*a*, p. 37, *c*, pp. 94, 227). Although some superposed streams are found in the Waterpocket flexure, where the Tertiary strata have been stripped from it (*a*, p. 288), the water-ways are thought to be antecedent in nearly all cases (*a*, pp. 16, 17, *c*, pp. 73, 187, 204, 219); San Rafael river and Curtis creek, both of which cross the San Rafael swell, are instanced as particularly good examples of their class (*b*, p. 63). Most of the great Miocene denudation was performed in a humid climate; then there was a gradual desiccation, as a result of which a number of tributary streams disappeared in Pliocene time, leaving untrenched valley floors high above the present canyon bottom (*c*, pp. 99, 194, 201); to the surviving streams of this dry period belongs the erosion of the narrow canyons and the steep cliffs (*a*, pp. 22, 23, *c*, pp. 223, 227). A temporary return to a humid climate occurred in the glacial period, and certain ravines on the Kaibab and Paria plateaus were then carved (*c*, pp. 196, 202).

In brief, the work of denudation in the Grand canyon district seems to require two cycles of erosion: the first, initiated by a broad uplift, had advanced well towards old age under a humid climate when the second, characterized by an arid climate, was introduced by another broad uplift complicated by certain dislocations; the second was subdivided into two episodes by a pause in the uplift, the first episode having approached maturity, while the second has not passed beyond youth.

The work of other observers, chiefly Gilbert, Howell, and Walcott, will be referred to further on.

THE ROCK SERIES. — The following figure of the rock series is here introduced for the convenience of the reader. It is compiled from reports by Dutton (*a*, *c*) and Walcott (*d*, p. 50), to which the brief article by Frech may be taken as supplementary.[1]

The strata exposed in the canyon walls reach up to the top of the Aubrey; those in the terraces of the High plateaus reach down nearly to the base of the Trias. The weak beds of the lower Trias and the Permian, with the resistant Shinarump sandstone between them, occupy the border between the base of the great terraces and the stripped surface of the upper Aubrey which extends over so large an area of the plateaus adjoining the Grand canyon.

LOCAL NAMES, MAPS, ETC. — Our habit of accenting the antepenultimate syllable of Indian words, whose original accent is on the penult, leads to a mispronunciation of a number of names for local features adopted by Powell, Dutton, and others in the Grand canyon district. The following list compiled from various sources may serve a useful purpose in preserving something of the original sound of these words, as well as in giving their meaning, along with that of some English names: —

Aubrey: The name of an army officer, given to a valley southeast of the Shivwits canyon, and extended by Gilbert to the line of cliffs north of the valley and to the upper Carboniferous strata in the cliffs (*a*, p. 177).

Coconino: (Variously spelled Cocanini, Coanini, etc.). Name of a forested plateau south of the Kaibab (Merriam, p. 35).

Grand Wash: "In this wide valley are several lines of drainage, of which the main one . . . is called the 'grand wash.' These washes generally have the cañon form — flat, gravelly bottoms, sloping talus, and steep escarpment above" (Marvine, p. 196). The same name is applied

---

[1] The name, Vishnu, given to a spur on the Kaibab wall by Dutton (*c*, p. 148) and applied to the crystalline schists in the bottom of the canyon by Walcott (*d*, p. 50), is to be regretted as out of place in the occidental world. Unkar and Chuar, as subdivisions of the Grand canyon series, Shinarump as a dividing member between the palæozoic and mesozoic series, Kaibab, Kanab, and the rest for the blocked plateaus, Toroweap and Paunsagunt for valleys, have much local flavor, however barbarous and ungraceful they may sound to our ears. But Shiva's and Vishnu's temples as names for pinnacled spurs of the Kaibab in the canyon wall, and Vishnu as a name for the fundamental rocks, buried by the plateau-making strata, are unnaturalized foreigners. The Vishnu schists in the desert bottom of the Grand canyon are as inappropriately named as Diana's baths in the cold White mountains of New Hampshire.

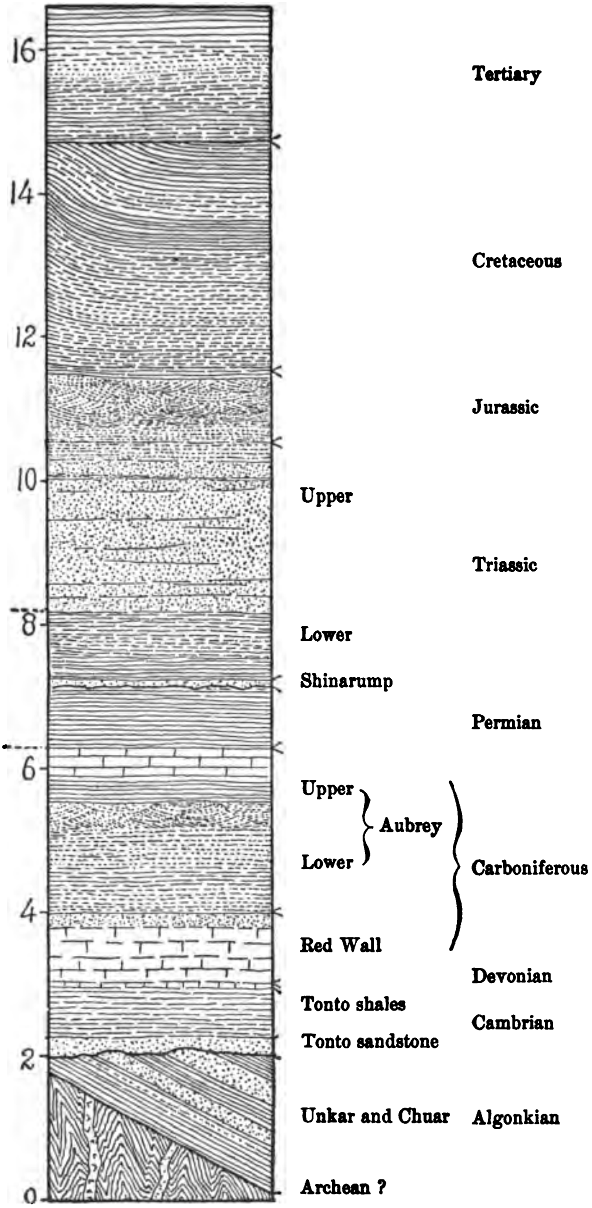


FIGURE 2.
Columnar section of formations in the Grand canyon district.

to the fault beneath the valley floor and to the great cliffs of the Shivwits plateau bordering the valley on the east.

Hurricane Ledge: "It is related that a storm overtook a party of Mormon officials while attempting to explore a route for a wagon road up a gulch which comes down from the upper country, and hence its name" (Powell, *a*, p. 187). The same name is given to the fault which determines the "ledge" or cliffs along the western border of the Uinkaret plateau.

Kaibab: "Mountain lying down" (Powell, *a*, p. 185). The highest plateau bordering the Grand canyon.

Kanab: "Willow" (Powell). Name of a tribe, a creek, a plateau, a canyon through its middle, and a town on the creek.

Paría: "The Ute name for elk" (Dutton, *a*, p. 253). A Triassic plateau east of the Kaibab, and a creek and canyon in it.

Shinárump: "Capping the cliffs, we find conglomerate, over which are scattered many fragments of silicified wood, known to the Indians as the arrows of *Shin-au'-av*, or *Shin-ar'-ump*" (Powell, *a*, p. 190). "The weapons of Shinav, the wolf-god" (Dutton, *a*, p. 147). A conglomeratic sandstone at the bottom of the Trias.

Shi'-vwits: Shiv signifies spring; Shivwits, the people of the springs (Powell). This word is spelled Shiwits, Sheavwits, Scheavwits, in various reports; the spelling here adopted being given by Powell (*a*, p. 128). The westernmost of the blocked plateaus.

Tonto: Spanish name of an Indian tribe, meaning "fool;" given by Gilbert to the basal sandstones of the Palæozoic series.

Toro'weap: "A clayey locality" (Dutton, *a*, p. 30). The valley between the Uinkaret and Kanab plateaus, probably so named from the fine silt deposited on the valley floor back of Vulcan's throne.

Uinka'ret: "Pine mountains" (Powell, p. 199). One of the blocked plateaus, capped with many volcanic cones and flows.

The chief features of the district are shown on eight sheets of the topographical map published by the United States Geological Survey: St. Thomas and Camp Mohave, Nev., Mt. Trumbull, Kaibab, Echo cliffs, Diamond creek, Chino, San Francisco mountain, Ariz.

Geological maps are given in Dutton's reports on the High plateaus and on the Grand canyon.

The drawings from which the illustrations of this article are reproduced can make no claim to accuracy of detail. They are made up from hasty sketches in which but little more than an outline was recorded. They err, as a rule, towards too great regularity of structural features, as in the view of Vermilion cliffs of the Paria (Figure 5). As a whole, they are diagrams rather than pictures.

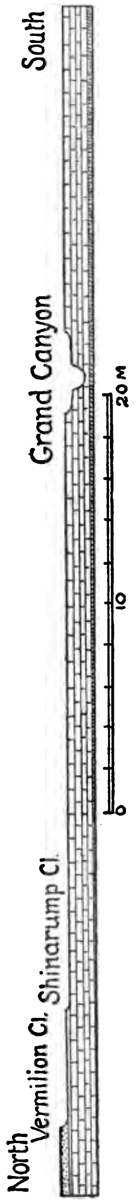


FIGURE 3.

North-south section through Kanab plateau; vertical and horizontal scales about the same. Reduced from Dutton (c).

The Great Denudation.

TWO CYCLES OF DENUDATION. — Some time before our excursion I had heard doubts expressed by a competent and critical observer as to the necessity of postulating pauses in the uplift of the region in order to explain the production of the existing topography of the Grand canyon district. These doubts were based on the close association of the general surface of the plateaus bordering the canyon on the north and south, and of the floor of the esplanade, with certain resistant strata; the first with the upper Aubrey, the second with the Red wall, as indicated in Figure 3. Omitting consideration of the esplanade for the present, let us consider the possibility of producing the broadly denuded plateau and the sharply entrenched canyon in one cycle of erosion, introduced by an essentially continuous uplift, without significant pause during the movement or supplement after its close.

It is here assumed that the normal progress of erosion in a single cycle demands the relatively rapid deepening of the main valleys by corrasion, and the correspondingly early attainment of a graded slope along the valley bottoms; a weathering of the valley walls, slower at first than the deepening of the valleys but faster afterwards, yet always at a decreasing rate; an associated but on the whole a slower series of changes along the minor water-courses; and with the progress of all these processes, a gradual advance of rapidly awakening activities to a phase of maximum development, followed by a much longer phase of relaxation and a very gradual attainment of the remote and ultimate phase of rest. The assumption of a still-stand of the land during all these systematic changes is accepted temporarily, but abandoned as soon as need be in order to meet whatever other conditions may be demanded in any particular case. The question here at issue regarding the sculpture of the Grand canyon district is between an essentially single uplift, rapid or slow but continuous, on the one hand, and two uplifts separated by a long period of denudation on the other.

It is evident that a broad denudation of the upper members of a stratified series can be contemporaneous with a narrow trenching of the lower members only if the former are relatively weak and the latter resistant. The plateau series is not so simply arranged, for among the strata that have been broadly denuded are the heavy and resistant Triassic sandstones which still stand forth in strong and steep cliffs along their line of outcrop north and east of the Grand canyon; while in the walls of the canyon, especially in the Kaibab section, there are two heavy series of relatively weak strata, the upper Tonto and the lower Aubrey, which have already retreated to partly graded slopes. The upper Aubrey limestone and sandstone and the Red-wall sandstone and limestone, to whose strength the maintenance of the plateau would have to be credited on the hypothesis of a single cycle of erosion, do not appear to possess any extraordinary resistance in excess of that of the heavy strata which make the retreating cliffs north of the canyon; and the weak members of the higher series, occupying the slopes between the retreating cliffs, do not seem to be notably weaker than the weak strata between the cliff faces in the canyon, — although exception to this statement should be made with respect to the unusually feeble blue clays of the lower Trias. Hence the canyon ought to be much wider than it is, or the northern "terraces" (cliffs) ought not to have retreated as far as they have, if the whole erosion had been accomplished in one cycle. We are thus held to the conclusion that the broad denudation of the plateaus must have been far advanced in an early cycle before the incision of the canyon was begun in a later cycle of erosion.

These considerations lend direct support to Dutton's view that there were two periods of uplift in the Grand canyon district, but it is desirable that some additional evidence of the verity of this view should be found in the shape of facts that are less immediately related to postulated conditions than are those thus far mentioned. Four groups of facts of this kind may be noted here, and a fifth will be presented in the account of the canyon in a later section.

The Mature Valleys of the Kaibab and Coconino Plateaus. — The upper Aubrey limestone caps the Kaibab plateau and the high ground opposite to it south of the canyon, to which the name, Coconino plateau, has been given. Powell refers to the southern highland as a "companion, or twin plateau" of the Kaibab, but a separate name is needed for it not only because the Grand canyon is cut down between the two plateaus, but also because they are separated by a strong monoclinal flexure with dip to the northeast, of which some account will be given in a later section.

The limestone capping of these plateaus is maturely dissected. Broad-floored, well-graded valleys with gently sloping sides ramify through the uplands in the most perfect manner, presenting a maturely developed form even to their heads; and this in spite of the fact that they are nearly always dry, for the wash of waste down their sides and along their floors is accomplished only during the rains and thaws of winter and the occasional showers of summer. It was of the southern or Coconino plateau that Newberry wrote: "The surface has been considerably modified by erosion, and now presents many broad and shallow excavated valleys" (p. 58). Dutton describes the Kaibab plateau as undulating "with rolling hills and gently depressed vales." The valleys are open-floored with gentle descent; they are innumerable, covering "the whole broad surface of the plateau with an infinite network of ramifications" (*c*, pp. 131, 134). Our party saw these well-established drainage ways both north and south of the main canyon, and we were much impressed with the maturity of their graded sides and floors, in contrast to the youthful expression of the precocious canyon. Plate 2 shows one of these mature valley floors in the Coconino plateau: a hill and farm of the farmer ant are in the foreground. If the upper Aubrey were so resistant as to have prevented the widening of the canyon while the heavy Triassic sandstones were stripped away for scores of miles on the north and south, no such mature valley system should be carved in the stripped Aubrey surface.

Furthermore, the contrast between the rapid wasting of the cliff in the canyon walls and the slow change of the mature valleys on the plateaus strongly suggests that the two processes represent different cycles of erosion. Dutton notes that, on the Kaibab rim of the canyon, "we often find an old ravine suddenly cut off on the brink of an abyss, and the continuation of the same ravine is seen upon the other side of the amphitheatre" (*c*, p. 170). A similar encroachment of the canyon upon the mature valleys of the Coconino plateau may be seen in the neighborhood of Hance's camp. We could also see, when looking up the canyon from the southern rim at Cameron and Berry's, that the upper Aubrey cliffs which descend into the canyon from a detached part of the Kaibab plateau that lies south of the canyon are notched by wide-open mature valleys which descend eastward with the monoclinal flexure that terminates the plateau in that direction. The valleys evidently once had a greater extension headward, but they have now lost some of their upper length by the widening of the steep-walled canyon; thus recalling the relation existing between the mature centrifugal valleys of Mt. Mazama and the sharp cliffs of the caldera that holds Crater lake in southern Oregon. It is normal enough for the deep-cut canyon to encroach upon the heads of valleys that descend away from it; but if the upper Aubrey had been resistant enough to hold the canyon narrow while the Triassic sandstones were worn away for scores of miles on either side, we should hardly expect to find beheaded valleys of a mature form; yet such a relation would be easily explained on the supposition that the beheaded valleys still retain, little changed, a mature form that they acquired in an earlier cycle of erosion, while the main river has destroyed its mature valley of the earlier cycle by incising the canyon in its floor.

THE LANDSLIDES OF VERMILION AND ECHO CLIFFS. — If the erosion of the plateaus and the canyon had been accomplished in a single cycle, there should be at the present advanced stage in the cycle no signs of revival in the processes of denudation on the retreating cliffs of the plateaus. If, on the other hand, there have been two cycles, revivals should be of frequent occurrence and of systematic distribution. The wonderful series of landslides that occur along the base of the Vermilion and Echo cliffs, on the western and eastern sides of the great notch in the Triassic escarpment that heads up at Lee's Ferry, seem to be features of this kind. It is noticeable that these slides occur relatively near the river, while further away the cliffs have a much more mature profile, entirely without slides. Inasmuch as landslides are characteristic of the earlier and more energetic stages of a cycle of erosion, it seems probable that those here described should be associated rather with the reviving activities in the youthful stage of a second cycle than with the fading activities in the advanced stage of a first and single cycle.

The neighborhood of Lee's Ferry is especially interesting in this connection. Here the Carboniferous strata of the Marble platform[1] dip gradually northeastward and descend below the level of the river, and the removal of the weak Permian and lower Triassic strata causes the valley to widen thereabouts, so that it loses the canyon form that is so marked further up-stream in Glen canyon, where the river cuts the heavy Triassic sandstones, and farther down-stream in Marble canyon, where the river has reached the resistant Carboniferous sandstones and limestones. Had the river cut down its channel continuously in a single cycle of erosion, the retreat of the Trias on either side of the notch in

---

[1] It seems permissible in the interest of brevity to speak of this plateau as the "Marble platform," instead of as the "Marble canyon platform." In the same way, the Echo cliffs monocline will be called the Echo monocline.

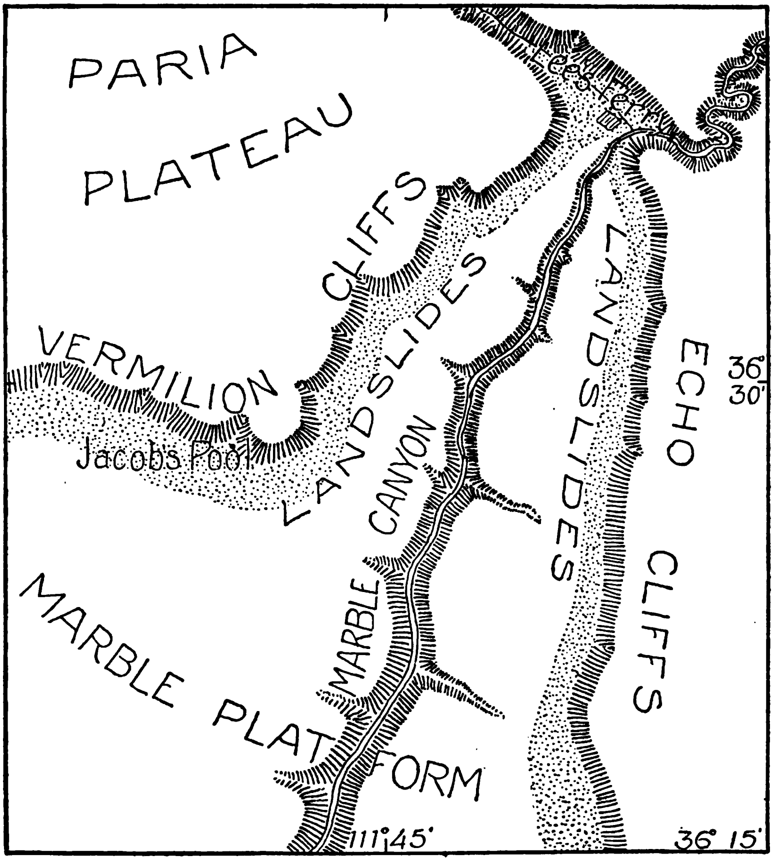


FIGURE 4.
Sketch map of the landslide district, southwest of Lee's Ferry. Triassic escarpment, hachured, above Permian belt, dotted. Reduced from Dutton's Atlas.

the Triassic escarpment should by this time have given the bordering cliffs — Vermilion on the west, and Echo on the east — a relatively stable profile, such as they usually have elsewhere; but as a matter of fact, it is precisely in the notch of the escarpment that the cliffs are most unstable and that landslides are most numerous. The cliffs have not retreated here far enough to allow the weak underlying strata — especially the blue clays of the lower Trias — to be concealed beneath a graded slope; it is because the cliffs are sapped by the rapid removal of the clays that the landslides result. Yet twenty miles northwest of the river, in House-rock valley between the Kaibab and Paria plateaus, a graded basal slope is well established beneath the cliffs and no slides occur. The same is true along the foot of the Echo cliffs, twenty miles south of Lee's Ferry; the weak blue clays are there concealed under a well-graded monoclinal valley floor, and slides are wanting. It is only as the river is approached that the clays are laid bare, and that, with

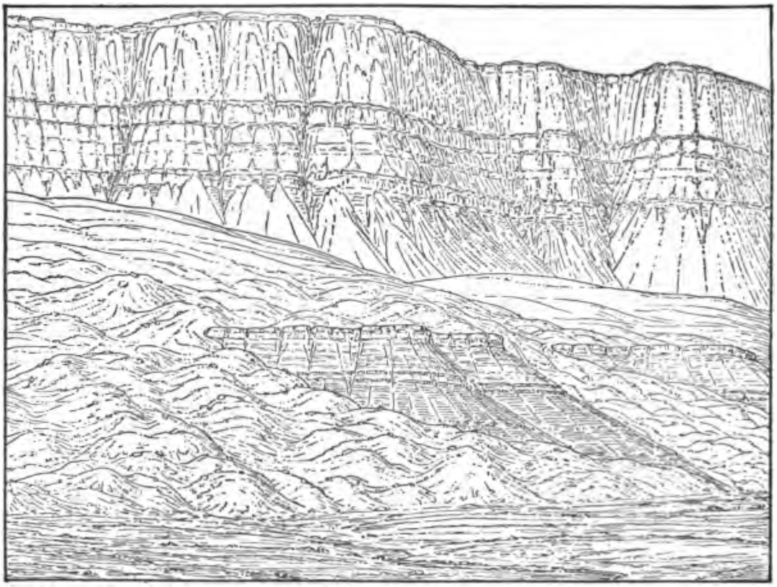


FIGURE 5.

Landslides of Vermilion cliffs. The Triassic cliffs rise to the rim of the Paria plateau. Monoclinal slides lie on the Shinarump bench, one of whose promontories is seen in the centre and another on the right, half smothered in tumultuous slides that descend to the plain of Marble platform in the foreground. Drawn from rough sketch.

their appearance, huge landslides become abundant. Just the reverse relations should obtain if the erosion of the region had been accomplished in a single cycle.

Imposing as these landslides are to one who follows the road along the base of the cliffs, they must be considered only as subordinate details among the colossal cliffs and platforms of this large-featured region, for no mention of them is found in the reports of Powell, Gilbert, and Dutton, although all these observers describe the Triassic escarpment from which the slides have slipped down. Some further account of them may therefore be given here.

In the Vermilion cliffs of the Paria plateau bordering the northern or middle part of House-rock valley, the upper members of the Triassic sandstone retreat somewhat, leaving the lower members to stand forth in a bench, and thus making two steps of mature expression in the descent from the plateau to the valley. Here the blue clays of the lower Trias and the underlying weak Permian layers are all concealed beneath the washed alluvium of the graded valley floor. If one looks down on the valley from the heights of the Kaibab on the west, an axial arroyo is seen to separate the wash of red Triassic waste on the east from that of gray Carboniferous waste on the west. In the southern part of the valley near House-rock spring, the blue clays begin to appear, and at once the lower bench of the cliffs breaks down here and there in normal landslide form; that is, the gentle dip of the cliff-making strata in the Paria plateau is steepened in the slide, so that the fallen mass takes the form of a ridge, more or less shattered and disordered, yet with a monoclinal structure apparent enough; the back slope of the ridge descends to an uneven depression along the base of the refreshed cliffs, while the outcropping face of the ridge descends to a confused mass of jumbled mounds in which the weaker basal strata are greatly disordered. The monoclinal slides become more nearly continuous and gain a formidable volume near the southern corner of the Paria about Jacob's pool; the harder strata that once formed the lower bench of the cliffs have here dropped down several hundred feet; but their forward movement is much greater, often being the better part of a mile. Passing around to the southeastern face of the Paria, the lower part of the cliffs consists of Permian strata, and the Shinarump sandstone (base of Trias) caps a conspicuous basal bench and cliff, splendidly carved. Here the slides are of two types. If their forward movement does not carry them over the edge of the Shinarump bench, they preserve the relatively orderly monoclinal form already noted; but when the slides advance far enough to fall over the bench, they flow down its frontal slope and sprawl out on the platform beneath like gigantic lava floods, as in Figure 5. The streams of rock-waste sometimes descend by a re-entrant notch in the front of the bench, like the lava flows in the notches of the upper Aubrey cliffs on the west side of Toroweap valley; they sometimes advance in large volume and cascade over the front of the bench, smothering salient as well as re-entrant of the Shinarump. The different colors of successive strata are normally arranged in orderly bands on the face of the cliffs; reddish gray sandstones at the top, then red-and-yellow-brown sandstones — vermilion seemed to us too strong a name for these cliffs, and "freight-car red" was suggested as a substitute — blue in the lower Triassic clays, chocolate brown in the Shinarump cliff, and banded creamy gray in the upper Permian slope. Something of banded colors may still be seen in the slides that have moved down and forward in orderly fashion to form the monoclinal ridges, but the color bands in the slides of greater forward advance become greatly confused when the slides sprawl down the Shinarump bench, and a most curious patchwork of reds, yellows, blues, grays, and browns is the result. Most of the slides seem to be old enough to have suffered some erosion since their descent, yet they are young and large enough to be very conspicuous elements in the landscape. They are easily recognized when seen at a distance of eight or ten miles from the summit of the Kaibab, where the road crosses it westward from House-rock spring.

If we now cross the river and go some twenty miles south of Lee's Ferry, the blue clays are concealed under the evenly graded floor of a monoclinal valley that follows the foot of the Echo cliffs; the Shinarump sandstone rises on the western side of the monoclinal valley, so as to overlap the eastern part of the Marble platform. The Triassic sandstones are, however, bolder in this part of the Echo cliffs than in the Vermilion cliffs of the northern part of the House-rock valley; they here expose a larger proportion of bare rock cluttered over with scanty and very coarse waste, not of orderly enough arrangement to be called a talus. Passing northward towards the river, the Shinarump sandstone crosses the valley obliquely as a low ridge, thus shifting from a cuesta-like attachment on the border of the Marble platform to a basal bench and cliff at the foot of the Echo cliffs; at the same time, the monoclinal valley shifts from the blue clays of the lower Trias to the weak Permian strata. Thus the blue clays come to outcrop on the slopes beneath the red sandstones of the Echo cliffs, and at once the landslides begin.

They are not so large or so numerous as those by Jacob's pool in the cliffs of the Paria, but they are of perfectly similar development when they occur. At first only forming monoclinal ridges above the Shinarump bench, they soon sprawl forward and downward on the broad platform beneath the bench. Among many others, one sprawling slide that advances at least a mile is a very striking feature to the traveller who follows the monoclinal valley road northward towards Lee's Ferry. When first seen at a distance of eight or ten miles, the slide seems to be a vari-colored ridge or spur, stretching forward in abnormal position from the base of the Shinarump bench; on a nearer view, its origin is evident enough, and when seen from in front, so that its full breadth is recognized, its lower part takes the form of a huge paw, below a wrist that is narrowed at the fall over the bench. We did not recognize any wrinkles ploughed up in front of the slides, such as Russell has described in association with certain great landslides in Washington (b. 47).

All this seems inconsistent with the scheme of one cycle of erosion, but perfectly consistent with the scheme of two cycles: the first having witnessed the development of a floor of weak Permian and lower Trias over the northeastern part of the Marble platform, with a border of maturely stable cliffs of Triassic sandstones on the north and east; the second having witnessed the incision of the Marble canyon, along with which came a rapid removal of the weak Permian strata down to the more resistant Carboniferous members, and with this an accelerated recession of the Triassic cliffs in the Lee's Ferry angle. It may be well to say again that the "scheme of one cycle" is an essentially single and continuous uplift, during and after which the denudation of the region has been accomplished in a single and persistent effort of the destructive forces; while the "scheme of the two cycles" involves two uplifts separated by a pause of relative quiescence, during which the great denudation of the plateaus was well accomplished; the incision of the canyons, the removal of weak strata from the denuded plateaus, and the revival of certain activities, such as have just been described, being the result of the second uplift.

THE MIGRATION OF CERTAIN DIVIDES. — Among the minor evidences of a modern revival of erosion, mention may be made of two examples of migrating divides in localities where a stable water-parting might have been expected if the erosion of the region had been accomplished in a single cycle.

Divide near Pipe Spring. — One example of this kind lies in the weak lower Triassic area west of Pipe spring and south of the Vermilion cliffs. It is crossed by the road leading from Kanab and Fredonia to St. George. The divide does not here separate well-defined valleys, but marks the boundary between two long and broad graded platforms of gentle declivity, one slowly descending eastward and southeastward to Kanab creek, the other westward to a dry branch of Virgin river.

The eastern platform heads westward in a sharp slope or "wall" of weak lower Triassic shales, two or three hundred feet high and locally carved into bad-land spurs, forming a great westward curve, as if a large bight had been gnawed into the head of the western platform, whose border is appropriately concave. Evidently the eastern slope is gaining area by undercutting the western. When we saw first this wall on looking west from Pipe spring, it was perplexing, as there was no structure known in the lower Trias by which it could be explained; and moreover its even profile, descending gradually to the south, bevelled the gentle northern dip of the strata in a curious fashion (Figure 6). But later in the day, when we looked northward to the divide from a point on the road between Pipe spring and Mount Trumbull (S, Figure 6), the origin of the wall was easily discovered. The two graded platforms were then seen in opposing profiles, the eastern heading under the western, as in Figure 7. Indeed, the northern part of the western platform could be seen to extend several miles eastward around the head of the eastern platform, forming a bench that obliquely ascended the front of the Triassic cliffs independent of structural guidance, until it must have been a good thousand feet above the eastern platform. I have never seen so fine an example of the relation between two drainage slopes, one encroaching on the other. It was a disappointment that our hurried movement made closer study of this area impossible.

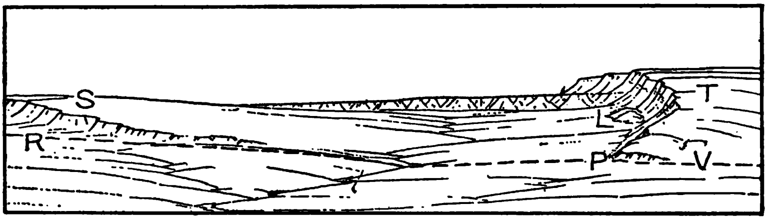


FIGURE 6.

View from east of Pipe spring, showing "wall" of migrating divide in the background. P, Pipe spring; T, Triassic plateau; L, landslide; S, Shinarump mesa; V-R, Sevier-Toroweap fault-line. Constructed from map and sections.

It is noteworthy that here, as in the neighborhood of Lee's Ferry, landslides have taken place where the blue clays have been uncovered by the encroachment of the eastern platform on the base of the Triassic cliffs. This was the case just west of Pipe spring, where the former head of the western platform has been deeply undercut. The blue clays were seen here and there along the base of the refreshed cliffs, and several landslides were noted in the same small district (L, Figure 6).

Relation of the Pipe Spring Divide to the Pipe Spring Fault. — Another peculiar feature of the eastern platform near Pipe spring is that it crosses the line of the Sevier-Toroweap fault (see that section) with unbroken grade, and that its descent is against the heave of the fault; that is, from the relatively depressed block of the Uinkaret to the relatively uplifted block of the Kanab plateau. No topographic indication of the fault is preserved at this locality, because the weak lower Triassic shales on the west are brought against the weak Permian shales on the east. The obliteration of the fault, as far as the relief of the surface is concerned, is an unusual feature of the plateau region, according to Dutton; for while he noted the obliteration of the Shinarump escarpment in the neighborhood of Pipe spring (*c*, p. 80) he did not connect its disappearance with any dislocation, and he elsewhere remarked that "every fault in the district is accompanied with a corresponding break in the topography" (*c*, p. 130). It should be stated that we identified the geological formations mentioned here and elsewhere entirely by their location, their lithological features, and their succession, as described in Dutton's reports, which in this way, as in so many others, were of the greatest service at every turn. Most of the formations are

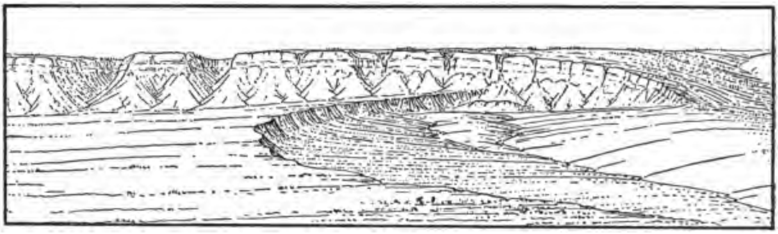


FIGURE 7.

View north near Pipe spring. Vermilion cliffs of Triassic plateau in background; the eastward dip of strata toward the Sevier-Toroweap fault-line is seen on the right, Pipe spring being near the end of the cliffs. The "wall" of the migrating divide sweeps through the middle of the landscape. Drawn from a sketch.

astonishingly bare of fossils; we saw only an occasional Productus in the limestones of the Kaibab.

The migrating divide between the two platforms near Pipe spring seems to indicate a recent and active revival of a contest that should, in a single cycle of erosion, have been settled long ago, but that might, on the other hand, be still in progress in the present youthful stage of a second cycle following the late maturity or the fine old age of the first. It is as if the news of the uplift that enabled the Colorado to incise its canyon beneath the plateaus had but lately reached the Pipe spring district. We may, therefore, suppose that a stable divide between the western branches of Kanab creek and the eastern headwaters of the westward drainage once existed somewhere to the east of the present unstable divide. If the stable divide were reconstituted in the position indicated for it by the remnants of the west-sloping graded platform, the east-sloping platform would necessarily stand above the level that it occupies to-day. This would demand the reconstitution of a graded Permian platform several hundred feet above the level of the Kanab plateau southeast of Pipe spring, a position that is entirely consistent with certain expectations as to the altitude of the ancient lowland of denudation produced in this neighborhood by the long-continued denudation of the first cycle of erosion, as will be shown further on. A reason for the present advantage of the eastern drainage may be found in some slight tilting associated with the uplift by which the second cycle was introduced; or it may be found in the lower stand of the resistant upper Aubrey strata in the nearly level structures of the Kanab plateau than of the same strata on the somewhat upturned western side of the Uinkaret plateau; but no decision can be announced without much more field work. The evidence furnished by this example of a migrating divide as to the date of the Sevier-Toroweap fault will be considered in connection with the fault lines.

The Cedar Ridge Divide under Echo Cliffs. — A second example of a migrating divide occurs in the monoclinal belt of the weak blue lower Trias clays already described as running along the base of Echo cliffs. The belt is followed by a wagon-road from Tuba to Lee's Ferry, first slowly ascending the graded floor of a south-discharging monoclinal valley, then slowly descending the graded floor of a north-discharging valley; the divide between the two valleys being known as Cedar ridge. The divide is, however, not a ridge in any proper sense. The southern valley undercuts the head of the northern one, and the two are separated by an abrupt southward slope, exposing the blue clays that are elsewhere completely hidden under alluvium (Figure 8). It is very clear that the southern valley is in process of being lengthened by headward growth or retrogressive erosion at the expense of the northern valley. Southward from the divide, there are terraces on the side of the deeper valley, attesting the once greater height of its floor. It was not possible for us to determine surely any local or general cause for the change that is here so actively in progress. It may, perhaps, be independent of the uplift in response to which the larger streams have cut down their canyons; nevertheless, we seem to have here as before a revival of activities that should have long since become quiescent if the erosion of the region had resulted from a single uplift.

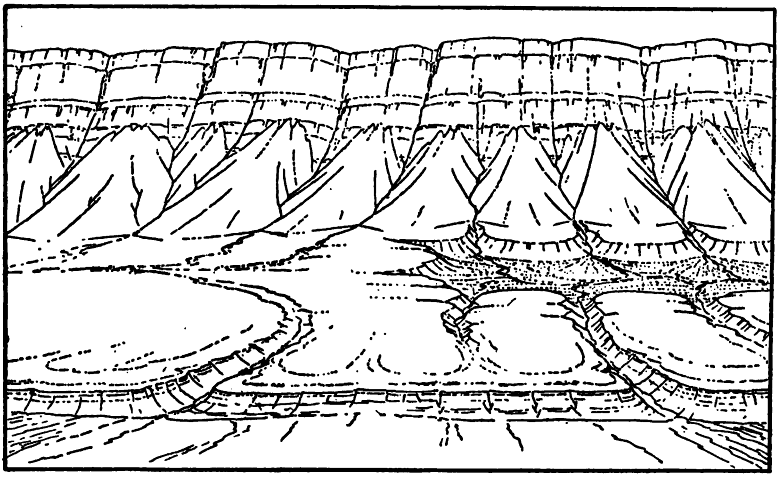


FIGURE 8.

Migrating divide at "Cedar Ridge" under Echo cliffs. The geological section here seen includes weak Permian strata under the Shinarump sandstone in the foreground; weak Triassic strata in the monoclinal valley at mid-distance, and the heavy Triassic sandstones of Echo cliffs in the background. The valley with shaded floor on right (south) is encroaching upon higher-floored valley on left (north). Constructed from field notes.

It may be that a similar migration is in progress at the divide between the northward and southward drainage of the monoclinal Houserock valley, but as this divide lay several miles north of our road we could not examine it.

Migrating Divides in Arid Regions. — It should be recalled in this connection that the migration of divides in general depends only indirectly on the action of streams; it is directly the work of weathering, creeping, and washing on the slope above the head of some deep-cutting stream. Water acts on such a slope only at time of rains and thaws. All this is strikingly illustrated in the plateau region, for here even the stream beds are habitually dry, and the whole process of rain and stream washing is intermittent and exceptional. But when the streams work, they work furiously, as is proved by the coarse stony fans of gentle slope at the ravine mouths on the flanks of the Kaibab and elsewhere. A very striking example of this kind was seen at the mouth of a ravine near the road from Flagstaff to Tuba, about ten miles southwest of the Little Colorado crossing. The ravine was sharply eroded in the sloping monoclinal surface by which the uppermost Aubrey layers descended eastward under the red shales and sandstones of the Permian; the lower ground opposite the mouth of the ravine was strewn over with huge limestone boulders that had been swept forward at time of flood.[1]

On the bare clay slope of Cedar ridge and on the red shale wall west of Pipe spring, erosion is accomplished by weathering and rain-washing rather than by stream corrasion. In spite of the aridity of the plateau climate, rain-washing is important; for the general absence of vegetation allows a single shower to effect a significant amount of work. The bare slopes retreat speedily, and the gentle grade of the valley floor or platform at the base of the slope is actively prolonged headward. The processes here at work resemble very closely those by which the recession of cliffs is accomplished: little destructive work is done on the graded platforms above or below the bare cliffs; nearly all the erosion is effected by the erosion of the cliff face and under-slope, as Dutton has pointed out (*c*, pp. 64, 221). But while cliff faces are determined by the outcrops of resistant strata, the bare slopes at the divides above described are independent of structure and are determined only by the difference of altitude of two graded valley floors or platforms. The bare slopes retreat rapidly while the graded platforms are hardly changed.

There is no reason for thinking that the average declivity of the bare slopes at these divides is notably different to-day from what it long has been or what it long will be. Hence there should be some systematic relation between the descent of waste from a bare slope and the removal of waste on the graded platform beneath; and the relation must evidently be one of equality. The slopes have been described as "bare," and so they are in a first general view, but in reality they are cloaked with somewhat loosened clay or shale, a little displaced from its normal position, still revealing the general attitude of the strata, yet masking the finer details of bedding. It must be supposed that the creep and wash of loosened waste from the slopes just suffices to keep the wet-weather streams busy when they are running in the channels on the graded floor; and hence that we here have one of the many examples of a natural equilibrium between capacity for work and work to be done. Similar examples of equilibrium probably occur between the descent of waste on certain dissected mountain slopes and the removal of the waste across the graded rock-floor platforms that stretch forward from the mountain base, as described by Penck for the subarid mountains north of Madrid in central Spain (p. 132) and by McGee for the arid mountains of the Sonoran district of Arizona and Mexico (*b*, p. 91, Plate 12). The basal angle between the slope and the platform seem to be more sharply defined in arid than in humid climates, probably because of the different values of the various agencies for soil production and removal in the two cases.

---

[1] It may be noted that if the transition here noted from limestone to yellowish and red shales be taken as marking the division between upper Aubrey and Permian, then the boundary of these formations is placed about five miles too far east in this locality on sheet XXIII. of Dutton's Atlas of the Grand canyon district.

THE PERMIAN SCARPS UNDER THE SHINARUMP CLIFFS. — The comparatively small quantity of waste on the Permian scarps beneath the Shinarump cliffs of certain fine mesas in the northern part of the Uinkaret plateau suggests a recent revival in the process of sapping; for it is difficult to understand how cliffs that have receded as far as these — forty miles from the canyon — should not by this time have their under-slopes well sheeted over with waste, if the retreat had been in a single cycle. The Permian scarps are not always bare: for example, those enclosing a valley opened in the Shinarump mesa ten miles southeast of Toquerville, and extending from Sheeptrough to Workman spring (see Atlas of Grand Cañon district, sheet XX.), are cloaked with a considerable covering of waste, which here and there bears a mask of vegetation; but in this case the processes of erosion have been much delayed by a recent flow of lava on the valley floor (not shown on Dutton's map). The southern scarps of the same group of mesas, only about ten miles further south and without lava at their base, are very bare, exhibiting many delicately colored strata that maintain a horizontal course across beautifully varied spurs and ravines. The contrast between these two examples re-enforces the suggestion that the bare scarps may have been much better clothed with waste during some former pause in the activity of the erosive forces, and that their fresh exposure to-day results from a revival of these processes, such as is elsewhere manifested in landslides and in migrating divides.

The Development of Talus. — It must be confessed, however, that the development of talus-covered slopes in the arid region is a complicated problem. The quantity of talus material will vary (in so far as it comes from the capping cliff) with the relation between the thickness and resistance of the hard cliff-making strata above and the weak slope-making strata below. The texture of the talus will vary chiefly with the manner of retreat of the cliff-maker. The completeness of the talus cloak will vary with the stage of the cycle of erosion. Certain mesas, perhaps of Permian strata, seen from the Santa Fe Western Railroad, east of Winslow, have a very coarse and discontinuous talus of large slabs, derived from the strong but thin cliff-maker, which is there broken into great fragments by the rapid sapping of the weak strata in the slope. A lava-capped mesa of Permian under-slope, seen near the road between Flagstaff and Tuba about ten miles southwest of the Little Colorado crossing, has a very coarse talus. On the other hand, certain cliffs of massive red sandstone, on the line of the railroad east of Gallup, descended to the alluvial floor of their valley without any talus at their base. Dutton (*c*, p. 228) has suggested that such a relation may be explained by the burial of a normal talus under recently aggraded alluvium, thus assuming the talus to be an essential accompaniment of the cliffs. In the example east of Gallup, the absence of weak basal strata and the habit of massive sandstones to weather by crumbling, rather than by breaking into blocks, seemed to be at least as important factors as the accumulation of alluvium. That some cliffs are habitually free from talus is recognized by Dutton in his account of the Jurassic escarpment flanking the high plateaus: here "a notable feature is the absence of talus; or, if it be present, its very small proportions" (*c*, p. 36). What has been said in the section on the migration of divides regarding the retreat of bare slopes does not particularly apply here, because in the examples now under consideration, the scarps of weak strata are capped by harder strata; and the habit of such strata is to conceal themselves under a cloak of waste from their capping cliffs. Even in scarps of so small a measure of retreat as those in the Grand canyon, the weaker strata are often largely cloaked with talus, as is the case with the great slopes of the upper Tonto series in the Kaibab section, and in the slopes of the lower Aubrey that descend to the esplanade in the western part of the Kanab section. It is true that the Permian scarps of the northern Uinkaret are long, being from three to five hundred feet in relief, and that the Shinarump cap may be only fifty or a hundred feet thick. Nevertheless, the occurrence of considerable sheets of talus on the scarps in the valley east of Workman spring serves to show first that the Shinarump capping yields sufficient material to form a cloak; secondly, that the cloak will quickly accumulate if erosion is retarded at the base of the slope; and thirdly, that aridity of climate cannot account for the absence of talus on the bare scarps a few miles further south. Hence it seems that the bareness of these Permian scarps must be explained by the recent removal of a talus that once covered them.

Perched Boulders. — There are certain details connected with the problem of retreating escarpments that are finely illustrated southwest of Lee's Ferry, where the full height of the Permian scarps with their Shinarump capping is revealed. Here, as on the Uinkaret, the scarps are bare; the bareness is appropriate to the active recession of the scarps already indicated by the landslides of this neighborhood. Another item was noted. We frequently saw large blocks of sandstone, ten to thirty feet in diameter, evidently derived from the cliff above, and now perched on pedestals of weak shale a little distance forward from the base of the scarp, as in Plate 2. The perched blocks correspond to rock tables on glaciers. The pedestals are from three to fifteen feet in height; some of the blocks have lately fallen to one side, and the pedestals that once supported them are not yet wholly worn away. The top of the pedestals represents the height of the graded platform at the base of the scarp when the block rolled down from above. Since then the platform has been degraded by the height of the pedestals; at the same time, the scarp has been pushed back a decidedly greater amount, and at a rapid rate compatible with the absence of a talus cloak on its slope.

Spurs and Ravines. — The minute morphology of the carved scarps affords a pleasing study; it is a subject of subordinate importance, truly, yet perhaps as deserving of careful attention as the morphology of the leaves of plants. Where the mesa scarps have a straight front, the ravines descend in relatively direct and parallel courses with few branches. Each main ravine receives the waste from but a small length of cliff front above. The spurs are correspondingly simple, each one descending with little variety of form from top to bottom of the scarp, although with increasing relief downwards. But where a curved reentrant occurs in a mesa front, the ravines converge more or less distinctly towards the base of the scarp; several upper branches may unite in a single lower trunk, and thus the lower ravine receives the waste from a considerable length of cliff face; at the same time, many spurs fail to reach the base of the scarp, but terminate acutely between the forking ravines, as in Figure 9. On the other hand, where a projecting scarp or promontory stands forth, the ravines diverge, and a single spur at the top of the scarp may broaden and repeatedly divide in its descent, assuming a sprawling paw-like form, and including many short ravines that begin within it. Variations of this kind are repeated systematically over and over again in the Permian scarps. When the entire height of the spurs is only some four hundred feet, it may be hardly worth while to develop any special terminology for their different forms; but when one finds that very similar spurs with heights to be measured in thousands of feet occur on the dissected slopes of Mt. San Francisco, the value of a simple terminology becomes more apparent.

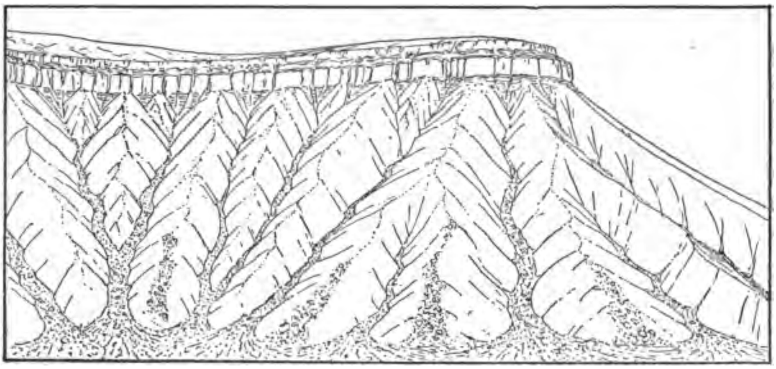


FIGURE 9.

Diagram of Permian spurs under Shinarump cliff. Tapering spurs on the left, split spurs on the right. Constructed from rough sketches.

There seems to be a curious alternation in the generation of spurs and ravines where a scanty or insufficient supply of resistant talus fragments from the cliff-maker is associated with an active erosion of the strata in the under-slope. As the coarse waste weeps and washes down from the cliff, it tends to avoid the spurs and to accumulate in the ravines. The bare spurs are then eroded more rapidly than the protected ravines, and thus a new ravine may come to be worn down the axis of what was a spur, while a spur stands forth where the ravine was before. A new supply of waste then gathers in the new ravine, while the older waste is in time removed from the new-made spur. Then the process is reversed. Several examples that seemed to be explainable in this way were noted on the Permian scarps east of Hurricane ledge; they are shown in diagrammatic fashion in Figure 9.

THE STRIPPED PLATEAUS. — The details presented in the four preceding sections concerning mature valleys, landslides, migration of divides, and bare scarps, all support Dutton's conclusion that the plateau surface north and south of the Grand canyon was "planed down to a comparatively smooth surface" (*c*, p. 119) before the erosion of the cañyon was begun; yet they can hardly be regarded as giving altogether independent demonstration of the conclusion, for some of them at least might all have arisen from some minor uplift of recent date. It is only when all of the elements of the problem are considered together, as Dutton often remarks, that a consistent explanation of the history of the region can be inferred; and then its erosion in two cycles seems essential. It is not desired to assert that two simple uplifts, separated by a long interval of perfect rest, constitute the diastrophic history of the region; but that a long period of relative rest and persistent denudation with respect to a comparatively constant baselevel occurred between earlier and later periods of uplift and dislocation. Each period of movement may have been of a considerable duration, complicated by pauses and intermittent displacements. Some of the earlier movements may have been separated by long pauses, of which no record now remains; but nothing less than a long period of relative quiescence before the last period of uplift seems sufficient to account for the great denudation of the plateaus and the narrowness of the rapidly widening canyon, along with the correlated details above described. The date of the faults, by which the plateau district is divided into great blocks, with respect to the earlier and later periods of denudation will be considered later.

The original uplift of the region, by which deposition was stopped and denudation begun, has been with good reason assigned by Dutton to Eocene time (*a*, p. 21, *c*, p. 217). The same author places the "period of quiescence" in "late Miocene or early Pliocene time" (*c*, pp. 77, 221); but in the absence of local fossiliferous deposits, by means of which the greater and lesser denudations can be strictly correlated with the geological time scale, I shall for the present use the terms, plateau cycle and canyon cycle, to name the greater and lesser periods in which the work of erosion has been performed; and so far as the events in the history of the district can be arranged in order, they will be thus dated.

Reasonable as the hypothesis of two cycles of erosion seems to be when all the facts are viewed together, it is difficult to point out representatives of the "very flat expanse" that was produced when the plateau cycle was interrupted by the uplift that introduced the canyon cycle. Dutton states that the older lavas of the Uinkaret and Shivwits plateaus cover considerable areas of Permian strata, which at the time of the early eruptions must have "constituted the general platform [of the district] in much the same way as the upper Carboniferous now does" (*c*, p. 107). Details concerning the Permian platforms are at present wanting; but if future observation shall show that they have no cap of resistant Shinarump sandstone, and that they are as level as is implied in Dutton's descriptions, then it may be fairly inferred that they were lowlands at the time of their burial under the lavas; for the Permian strata are too weak to permit of the production of a plain of erosion within their mass at a significant height above baselevel, such as might well enough occur on the upper surface of a more resistant formation. Accepting this conclusion provisionally, as the most probable one now obtainable, it is then reasonable to infer that the Permian lowland once extended far and wide, and that it was in fact part of the peneplain to which much of the region had been reduced at the close of the plateau cycle. To-day the peneplain on the Permian is preserved only where it was sheeted with lava; the Permian floor elsewhere visible north of the broad Carboniferous platform must be referred to the canyon cycle, as in the district southeast of Pipe spring. It will be an interesting matter for some future observer to inquire into the stratigraphic relation of the floors on which the older lavas rest in adjacent plateaus, in order to determine how they bear on the date of the faulting by which the plateau blocks are separated. Much more work on the ground will be needed before this elusive question can be definitely settled.

Since the uplift by which the canyon cycle was introduced, sufficient time has elapsed for an extensive removal of the weaker Permian strata from the plateau surface, wherever they lay within easy reach of the "wash" that must have been actively revived at the opening of the new cycle: "considerable masses of the Permian were then remaining, which have since been eroded," as Dutton puts it (*c*, p. 120). Even the resistant upper Aubrey strata, revealed by the stripping of their Permian cover, early in the canyon cycle, have suffered a significant amount of dissection, as seems to be the case over much of the Kanab plateau; but the dissection here is not so mature as that by which the higher Kaibab is characterized, as will be further considered later.

The graded Permian surface in the northern part of the Kanab plateau to-day may, therefore, be better explained as having been in large part newly developed with respect to existing local baselevels (such as sills of upper Aubrey at the heads of branch canyons) instead of as having been preserved with little modification since the close of the previous cycle. I am consequently inclined to dissent from Dutton's opinion that "the broad and slightly varied expanse" of the surface of denudation which "cuts the strata in such a way that the [low] hills usually consist of lower Permian strata lying horizontally, while the shallow valleys expose the Carboniferous" (*c*, p. 118) is a close representative of the broad lowland of denudation produced at the close of the plateau cycle. Truly, "the mean position of the surface of denudation is very nearly coincident with the dividing horizon between those two formations": and if "we successively visit districts considerably apart, we shall find in one of them [the southern] that the mean position of the surface of denudation is below that horizon so far that no Permian rocks appear in the hills; in the other [the northern] it is so far above it that no Carboniferous rocks appear in the valleys" (*c*, p. 118); truly also the gentle bevelling of slightly inclined strata over large areas is often accepted as evidence of peneplanation, as by Campbell and Mendenhall for the plateau of West Virginia (p. 483), and by Philippson for the plains of Russia (p. 40); but in the plateaus of the Grand canyon district another interpretation seems permissible. It should be noted that only two formations are referred to in the above-quoted extracts from Dutton's report; the lower one (Carboniferous) resistant; the upper one (Permian) relatively weak. These formations rise gently southward. The great Carboniferous platform (upper Aubrey) on either side of the canyon in the Kanab district, here chiefly under consideration, is free from Permian remnants over all those large areas whose drainage is actively tributary to the main river; while the continuous Permian cover, apart from certain large patches that are protected by lava sheets, is found only some distance north of the canyon, where the dip of the strata brings the Permian down to a level that is safe from erosion for the present, and that can be attacked only as the wet-weather streams cut deeper into the Aubrey sills on their way down branch canyons to the Colorado. Now, if the Permian were the resistant and the Carboniferous were the weak formation, or if the next overlying and resistant formation further north (Triassic) were also bevelled down to the Permian level, the bevelled surface would necessarily be regarded as a peneplain, at present uplifted and in process of dissection;

but no such conclusion seems compulsory in a case where only two formations are involved, and where the upper of the two is the weaker. It therefore seems legitimate to say that a peneplain, so far as one was developed at the close of the first cycle, lay in the Permian formation at some unknown height above the present plateau surface in the Kanab district; and that the Carboniferous platform as now exposed in the Kanab plateau is a stripped and somewhat dissected plain, with reference to whose northern margin the Permian plain of to-day is graded: the stripping and moderate dissection of the Carboniferous and the new grading of the Permian being the work of the canyon cycle. The Uinkaret and the Shivwits plateau seem to be susceptible of similar interpretation. The Marble platform also is probably to be regarded, like the Kanab and other western blocks, as a stripped structural surface. It must have been covered by baselevelled Permian and lower Triassic strata at the close of the plateau cycle, but these have been now for the most part stripped down to the upper Aubrey. In brief, the evidence for two cycles of erosion in the evolution of the existing topography of the Grand canyon district is not to be found so much in the general evenness of the great Carboniferous platform, beneath which the narrow canyon is cut, as in the great recession of the Triassic and other cliffs compared with the small width of the rapidly widening canyon, and in the minor phenomenon therewith correlated.

Dates of Displacements.

THE EASTERN FLEXURES: — Flexures appear to preponderate in the eastern part of the Grand canyon district, while faults are the chief form of displacements in the western part, as shown in Figure 10. It will be shown that there is much probability that the flexures are older than the faults as a whole, and that the displacements of both classes seem to deserve an earlier date than has been assigned to them in Dutton's reports.

The Earliest Flexures. — The Waterpocket and the Escalante flexures lie northeast of the field of our excursion, but as they are the only disturbances which have been regarded as pre-Tertiary, it is important to make some mention of them here. They involve Cretaceous strata, whose eroded edges are unconformably buried by the Eocene of the High plateaus on the northwest (Dutton, *a*, p. 43, pp. 280, 288, 294; *c*, p. 215; Gilbert, *c*, p. 10). The San Rafael swell, still further northeast (Dutton, *c*, Atlas, sheet 11), is described as of Miocene date, probably because of

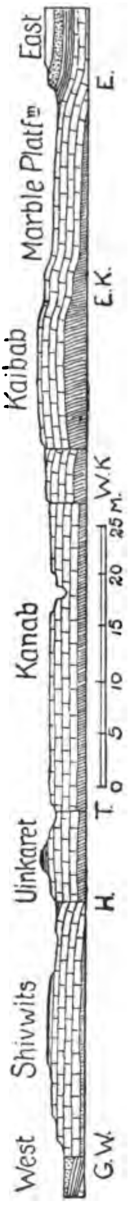


FIGURE 10.

East and west section of the Grand Canyon district, from the lower lands west of the Grand Wash fault to the Echo flexure. Vertical scale somewhat exaggerated. Modified from Dutton's section (*c*).

the roughly concentric attitude of the escarpment of horizontal Eocene on the northwest with the escarpments of the swell itself (*a*, pp. 19, 20); but it nevertheless seems permissible to class this dome-like uplift with the Waterpocket and Escalante flexures as having been formed in what may be called the Cretaceous-Tertiary interval, and as having been, like the flexures, greatly eroded before it was buried by Eocene deposition. True, the unconformity thus implied is nowhere preserved, for the Eocene strata have now receded to a distance of about forty miles from the centre of the swell; but some indirect evidence for their original unconformable extension over the eroded swell is found in the small amount of adjustment of two transverse streams to the domed structures, as will be more fully stated further on.

The Kaibab and the Echo (Paria) Flexures have been described as about contemporaneous with the broad uplift that introduced the erosion of the Grand canyon (*c*, pp. 192, 205), but they seem to be of older origin if one may judge of the date of their deformation by the recession of the Triassic cliffs that stand in association with them. This is shown as follows: The Triassic (Vermilion) cliffs have retreated at least twenty-five miles around the northern end of the Kaibab since its uplifting; and the same Triassic cliffs have retreated to close coincidence with the line of the Echo (Paria) flexure since its production, from whatever irregular line of front they had previously when the strata were horizontal. But, on the other hand, the upper Aubrey cliffs, enclosing the outer gorge of the canyon in the Kanab and Uinkaret plateaus, have retreated only two or three miles since the beginning of the canyon cycle. Surely then the Kaibab arch and the Echo monocline must be older than the beginning of the canyon cycle. Moreover, Walcott has called attention to the flexure of the east Kaibab monocline without fracture, and has concluded from this that a considerable load of overlying strata must have covered the Kaibab when the flexure was produced (*d*, pp. 60, 64); in other words, that the flexure occurred sometime before the close of the plateau cycle.

If this conclusion be correct, the crown of the Kaibab arch must have risen a thousand feet or more above a denuded lowland on the east and west at the close of the plateau cycle. The strikingly even skyline of the Kaibab, as seen from any distant point, is therefore to be regarded as indicating a stripped structural (upper Aubrey) plain, and not as a part of a once baselevelled surface, afterwards uplifted. The exposure of the arch to denudation during the later stages of the plateau cycle, as well as through so much of the canyon cycle as has yet elapsed, is indicated by the much greater dissection of its surface than that of the Kanab, which, as explained above, is best regarded as a stripped structural plain of the current cycle. The difference between the greater and less dissection of the two plateaus is indicated in Dutton's descriptions, for one is there spoken of as diversified by valleys which "cover the entire surface" (*c*, p. 134), while the other is said to be (except for deep canyons) "no more uneven than the rolling prairie of Iowa" (*c*, p. 124); and this contrast of form may be easily recognized on comparing sheets VIII. and XI. of the Grand Cañon Atlas. Another corollary of the early uplift of the Kaibab arch is that an open valley must have been eroded across it in the later stages of the plateau cycle. If this be true, then it must be further supposed that the rapid widening of the new and deep canyon in the current cycle has consumed all traces of the earlier valley.

The Crags of Echo Cliffs.—A peculiar feature of the Echo cliffs deserves brief mention. In looking along this great escarpment from the south, its crest at several points between Tuba and Lee's Ferry is seen to rise in serrated peaks with sharp slopes on the east as well as on the west, thus departing from its ordinary tabular form. We at first took the sharp serrations to indicate a local increase of dip, and on coming abreast of them were much surprised to find the dip practically unchanged from its uniformly moderate measure. The front view of the escarpment at certain points between the serrated peaks disclosed sags in the crest line that could not be explained by any local thinning of the cliff-making sandstones, for they seemed to maintain substantially a uniform thickness for tens of miles together. It was therefore suggested that the peaks and sags resulted from the occurrence of strike faults with small throw, torn on the slope of the monocline. As the retreating cliff face approaches such a fault, the crest becomes sharp and serrated, and strong eastward slopes locally replace the ordinary gentle eastward descent where faults are absent. Powell noted the sharp crags and relates them to the "line of displacement," but he did not specify the aid that local faults would give (*a*, p. 192). When the cliff face retreats still further, so as to remove the sandstones from in front of a fault plane, the crest line of the remaining cliff sags to a lower level than usual. It would be necessary to follow the crest of the escarpment for some distance in order to determine the measure of verity in this suggestion.

THE WESTERN FAULTS. — Attention may next be given to the fault lines of the Grand canyon district west of the Kaibab. These fall into the class to which Dutton gave a very late date: "None of them will go back of the Pliocene in age, and I think it probable that none of them will go behind the middle Pliocene" (*a*, p. 43). "Their formation seems to have been incidental to the uplifting of the platform which took place about the time the present Grand Cañon began to cut. . . . Before this epoch we know nothing of them" (*c*, p. 226). Some of the faults may now be considered in more detail.

The West Kaibab Faults. — Of the three faults indicated in Dutton's map along the western border of the Kaibab, we identified only the eastern one. It forms a fine wall, of generally graded slope and much scored by ravines. Its date is not easily determined, as it does not cross the cliff-making formations on the north until, according to Dutton, it joins the east Kaibab flexure. The recession of the cliff from the fault line here, as elsewhere, affords an uncertain measure of the antiquity of the faulting; for if the faulting occurred before the opening of the canyon cycle, much of the height of the present cliff may then have been fronted by weak Permian strata, since removed.

The Toroweap Fault. — The next displacement west of those which limit the Kaibab arch is the Toroweap fault. This is regarded by Dutton as for the most part of very recent date; at least part of its movement being later than the erosion of the broad-open flat-floored upper part of the canyon, called the esplanade, because the floor of the esplanade drops down to the west on passing the fault line; and later also than the eruption of a certain lava flow that was poured into the esplanade, because the lava also is dislocated by the fault (*c*, p. 94). On the latter point, I am unable to offer any evidence; but as the problem now presents itself, the dislocation of the floor of the esplanade does not seem to bear on the date of the fault; for if we regard the esplanade as dependent on structure, as will be considered further on, the break in its floor would occur at the fault line whether the fault was earlier or later than the erosion of the canyon. The small recession of the Red-wall cliffs in the Toroweap valley near Vulcan's throne (*c*, p. 94) is explainable by their relatively recent exposure in the canyon cycle, by the failure of erosion as yet to disclose any weak underlying beds, and by the protection of the base of the cliffs by lava floods, as will be more fully described further on in the section on the Toroweap. The location of this valley in close association with the fault line suggests that the fault originated before the valley was begun, that is, before the initiation of the canyon cycle; and this view is borne out by the strong recession of the Triassic (Vermilion) and Shinarump cliffs on the eastern side of what appears to be the same fault line in the neighborhood of Pipe spring. As my interpretation of the stratigraphy here differs somewhat from Dutton's, the case must be presented in detail.

The Sevier Fault Southwest of Pipe Spring. — The great Sevier fault is described and mapped by Dutton as coming southward from the High plateaus and ending near Pipe spring (*c*, p. 20), while the Toroweap fault is said to end northward at the head of the valley of the same name, twenty miles from the canyon (*c*, pp. 20, 93). A longer extension of the Toroweap fault is indicated by Powell, who briefly stated that where it "crosses the Vermilion cliffs" its throw "is only about two hundred feet;" but he does not specify that the crossing is at Pipe spring (*a*, p. 186). It happened that on our excursion we had good opportunity of seeing the general features of the Pipe spring district, where we noted that the cliffs formed on the Triassic and Shinarump sandstones were distinctly displaced with respect to what may be called the Sevier-Toroweap fault line. Hence, instead of curving the Sevier fault to the southeast and ending it near Pipe spring, as it is drawn on Dutton's map, it seems better to continue it to the south-southwest till it joins the known Toroweap fault. Where the fault-line thus extended crosses Antelope valley, a shallow depression in the broad plateau surface south of the Shinarump cliffs, its occurrence is not so easily proved as in the neighborhood of the cliffs. As indicated in Figure 11, both the Triassic and the Shinarump cliff-makers stand about ten miles further north on the heaved (eastern) than on the thrown (western) side of the fault near Pipe spring, thus indicating not only an important dislocation, but a relatively long time since its production. This is the rule of the region. Similar large measures of erosion since faulting are generally indicated by a break in the alignment of the Triassic and Shinarump cliffs wherever the fault lines cross them. Powell (*a*, p. 191), Gilbert (*a*, p. 51) and Dutton (*c*, p. 200) all recognize the greater recession of the escarpments of the heaved side of the faults as a general occurrence, but they do not explicitly connect the amount of recession with the date of faulting. The dislocation of the cliff front is, as Gilbert phrases it, "not due to any horizontal displacement along the line of fault, but merely to the fact that the eastern portions, being lifted higher than the western, became subject to different conditions of denudation" (*a*, p. 51). Near Pipe spring, not only have the cliffs of the eastern (Kanab) block receded ten miles since the faulting occurred: but ten miles is the excess of the recession of the eastern cliffs over that of the western; hence the chief movement of the fault here must certainly be of earlier date than the beginning of

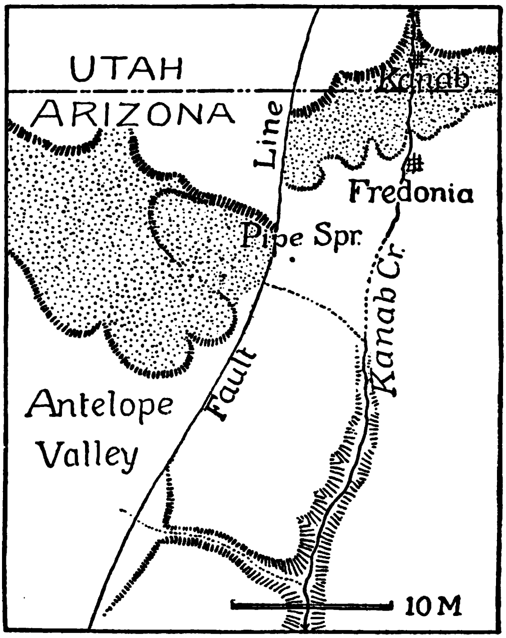


FIGURE 11.

Sketch map of the Pipe spring district, showing the Sevier-Toroweap fault. Weak lower Triassic strata, dotted; Triassic and Shinarump cliffs, hachured. Constructed from Dutton's map and original field notes.

the canyon cycle, however recent the latest of its movements may have been on the brink of the canyon.

Topographic Effects of Faulting obliterated or reversed by Erosion. — The continuously graded platform, sloping gently eastward across the fault line near Pipe spring and obliterating the topographic effects of faulting, has already been described. The fact that this platform is now gaining drainage at the expense of the west-sloping platform, strongly suggests a remote date for the displacement; had a recent movement taken place here, with uplift on the east, the westward migration of the divide could hardly be explained. A little further south, the Shinarump cliffs in the Uinkaret block, west of the fault line, overlook lower ground east of them, thus furnishing an excellent example of topographical relief standing in opposition to the displacement of the fault; evidently the result of the long action of erosion upon the unlike strata brought together by the faulting. Indeed, this part of the fault line offers many instructive illustrations of the difference between the geological and the geographical values of a fault. Geologically considered, the fault has a fixed value; geographically considered, the fault has a changing value. When the fault attains its full displacement, its geological history is completed, and its geological measure thenceforward remains constant. When the fault attains its full displacement, its geographical history is just begun, and thereafter its measure perpetually changes. The topographic features initiated by displacement may be more or less modified by contemporaneous erosion, but the young fault cliff will still be a tolerably regular feature, scored by growing ravines. Movement ceasing, erosion continues and the fault-cliff becomes lower and less regular. Where hard beds in the heaved block confront weak beds in the thrown block, the cliff consequent on faulting will last longest; where these hard beds are not underlain by weak beds (unless beneath baselevel), the cliff face will retreat most slowly from the fault line. Where weak beds are brought together, all topographical indication of the fault will soon disappear. Where hard beds in the thrown block confront weak beds in the heaved block, the topographic relief may come to contradict the throw of the fault, as is the case with the Shinarump cliffs above mentioned. But in time, all indication of the fault will be obliterated in the general reduction of the region to a peneplain, strong and weak rocks alike being laid low. If a general uplift of the region then occur, erosion may renew the fault-cliff topographically wherever strong beds adjoin weak ones, although no new movement takes place upon the fault plane. In such cases, the small retreat of the revived cliff from the fault line has sometimes given rise to the belief that the fault is of recent date, but it is evident that no such conclusion can hold. The revived cliff may be in the thrown-block, if the arrangement of the rocks favors such a result. A striking example of this kind may be seen in Tennessee (see Briceville, Tennessee, topographic sheet, United States Geological Survey), where the front of the Cumberland plateau is cut across by a northwest-southeast fault, the northeastern block being relatively uplifted; but to-day the surface is worn low on the weaker strata of the uplifted block, so that it is overlooked by the uplands of Carboniferous sandstones on the depressed block.

If these considerations are accepted, there can be little doubt that the Sevier fault continues in strong force beyond Pipe spring, as if to join the Toroweap fault, some thirty miles further to the southwest. Some topographical expression of the fault ought to be found in the broad floor of Antelope valley, beyond the Shinarump cliffs of the Uinkaret plateau, where the weak Permian of the Uinkaret block lies opposite the resistant upper Aubrey of the Kanab block. It is perhaps in this way that one may explain a west-facing bluff which extends about ten miles south of Antelope valley (Dutton, *c.* Atlas, sheet XXII.), but further study on the ground is needed before this can be assured. It is interesting to note, however, that the wet-weather drainage here is from the weaker beds of the thrown block eastward through a gorge in the bluff that is determined by the more resistant beds of the heaved block; a condition that is again entirely inconsistent with a recent movement on the fault plane.

The Hurricane Fault is not definitely dated in Dutton's report, but its southern part is thought to be of "comparatively recent origin," because "the amount of recession by erosion of the cliff of displacement is very small" (*c*, pp. 116, 117). Its northern part near Virgin river must, however, be old enough to have allowed a strong recession of the Triassic escarpment since the faulting; for the two parts of the Trias east and west of the fault line are now fifteen miles apart (*c*, pp. 42, 200); and as in the Sevier-Toroweap fault, the displacement of the cliffs is a measure not merely of their erosion since faulting, but of the excess of erosion in the heaved block over that in the thrown. The small amount of recession of the Hurricane ledge (Aubrey) from the fault line in the southern part of the Uinkaret plateau, as stated in the last quotation from Dutton, may be explained not so much by the recent date of the fault, as by the recent date at which erosion had opportunity of attacking the strata here concerned; for, as in the case of the Toroweap fault, until renewed uplift introduced the canyon cycle, it must be supposed that the strata in the Hurricane ledge of to-day were close to or even beneath baselevel, and hence out of reach of erosion. On the other hand, a branch of the main Hurricane fault cuts certain lava beds, — not the most recent ones (*c*, pp. 116, 117), — and this branch must be younger than the lavas, which in turn must at the oldest have been erupted late in the plateau cycle.

The Hurricane fault seemed to me to fade away just north of Virgin river. The line of great cliffs that comes up from the south here gives place to a monoclinal flexure, dipping to the west in sympathy with the throw of the fault; and a few miles further north the flexure loses importance, as far as we could interpret its structure in the view from the escarpment south of the river. A new displacement seemed to begin two or three miles to the west, rapidly increasing its throw northward and so continuing from Toquerville past Belleview, Kanarra, and beyond, where it sharply separates the Plateau province from the Basin range province. The southern termination of this displacement was not certainly determined. As a fault, it ends just south of Toquerville, but it may turn southwest and find a continuation in the anticline at the eastern base of Pine valley mountain. In any case it seemed entirely independent of the Hurricane fault proper. The course of Virgin river hereabouts is perhaps consequent upon the overlap of these displacements, for it lies close to the sag between them. It may be added that, although we had a fine view northward into the valley of Le Verkin creek from the rim of Hurricane ledge, we did not detect the lapse of the Permian and the unconformable overlap of the Trias on the Carboniferous, as noted by Howell (p. 285); but to assert the non-occurrence of these features would be going too far. The neighborhood of Toquerville offers an unrivalled field for special study. The village serves as a good base of supplies, the surrounding district is traversed by many roads and trails, stratified rocks range from Carboniferous to Tertiary, igneous rocks are present in good variety, the structural features are of unusual interest, denudation has been enormous, and the half-desert scenery is superb in form and color.

The Grand Wash Fault is said by Dutton to be no older than Pliocene (*c*, p. 191); yet the work of erosion after the fault had attained a strong measure of displacement would give it a much greater antiquity, for while a monoclinal slice of the Trias is preserved along its thrown (western) side, there is no Trias on the heaved Shivwits block for fifty miles

(Dutton, *c*, p. 200, Atlas, sheet II.). The Trias must have once extended eastward beyond the line on which the fault was broken; and the uplifted eastern extension of the formation must have been worn away after the faulting. On the other hand, a late movement on the same fault line has been thus far tacitly postulated, for the uplift by which the canyon cycle was introduced in the Grand canyon district does not seem to have extended with equal strength into the Basin range province west of the Grand wash fault line. But as I have not seen this district, it must be passed only with brief mention.

THE WESTERN MONOCLINAL FLEXURES. — The above review makes it probable that, however modern certain minor movements on the fault planes may be, the chief movements, by which, as Gilbert said, the adjacent plateau blocks were made subject to "different conditions of denudation," are of considerable antiquity. They must antedate the beginning of the canyon cycle. Yet the first deformation of the Grand canyon district is of still earlier date, for the faults with heave on the east were in a number of cases preceded by monoclinal flexures with heave on the west. The few exceptions to this rule of unlike movements do not seriously invalidate it. The east Kaibab monocline is torn into an east-throwing fault near the canyon; and similar small faults are suspected along the Echo monocline, as noted above. The Escalante flexure dips to the southwest, but its displacement is gradual compared to that of the Waterpocket, Echo (Paria), and east Kaibab flexures, which all dip eastward. A flexure with strong throw on the west is indicated for the western border of the Kaibab in Powell's general section of the district (*a*, p. 190, Figure 73); the displacement given to it is as great as that of the upper of the two east Kaibab flexures. Two west-dipping flexures on the west side of the Kaibab are shown by Gilbert (*a*, p. 51); but in the more detailed descriptions and sections given in Dutton's report (*c*, pp. 183–186, Figures 3, 4, and Plate II.), nearly all of the displacement on the west side of the Kaibab is accomplished by two faults, with hardly a tract of flexure; the gentle westward dip in the western half of the Kaibab highland — more pronounced to the north where faulting is changed for a west-dipping flexure — may suffice to warrant the use of the term "Kaibab arch," but it seems to be even less pronounced than the broad Escalante flexure. Where our party descended westward from the Kaibab by one of the greater ravines, west of Jacob's lake, the horizontality of the strata all the way to the main limiting fault was in strong contrast to the pronounced flexure of the eastern border. It may be, however, that both the western faults become flexures near their northern end, as is noted for one of them, above, and as is the case with the Hurricane fault proper, just north of Virgin river. But the only flexure on the western side of the Kaibab mentioned by Dutton is one by which the thrown beds are turned down as they approach the fault plane from the west (*c*, p. 128).

The northeast dip of the flexure that separates the Coconino plateau from the Kaibab is strongly marked. Strong eastward dips are observable on the lines of the Grand wash fault and of the great fault (almost in line with the Hurricane fault) north of Toquerville. The rule that the faults throw to the west and that the flexures throw to the east is therefore very generally obeyed.

The frequent association of flexures and faults on the same line is noted by several observers. Dutton described the downward flexure of the thrown beds in connection with the Hurricane, Sevier, and west Kaibab faults (*c*, pp. 41, 113, 114, 115, 128, 185, 186); while Gilbert (*a*, p. 54) and Marvine (p. 196) give diagrams of the Grand wash fault which exhibit the same feature. Dutton suggests that flexing preceded faulting (*c*, p. 115), and Walcott discusses a remarkable pre-Cambrian fault with throw to the west, on the line of which the east Kaibab torn flexure was formed in Tertiary time, with throw to the east (*d*, pp. 49–64). It seems probable that the prevailing coincidence of flexures and fractures may elsewhere, as well as in the east Kaibab example, be associated with faults of ancient origin, possibly in the pre-Cambrian foundation of the palæozoic and mesozoic strata, although it is only in the Grand canyon that this relation is open to study.

It is certainly remarkable that the distinct flexures of the Grand canyon district dip eastward so generally, while the faults have their throw to the west with almost equal regularity. In all cases where this relation obtains, the later movement by faulting was of greater measure than the earlier movement by flexing. It is further noteworthy that the unfaulted or least faulted flexures, such as the Waterpocket, Echo, and east Kaibab, lie to the east; while the distinctly faulted flexures lie to the west. It may also be remarked that, if the difference of date here inferred for flexures and faults holds true, it will be inappropriate to use the term "Kaibab structure" in the sense given to it by Powell (*b*, pp. 14, 22), and adopted by Gilbert (*b*, p. 86); namely, as a designation for a plateau that "primarily" surmounts lower ground on both sides. The greater part of the altitude by which the Kaibab surmounts the Kanab on the west is probably not a primary feature, but a secondary one, due to faulting after flexing.

The faults have already been referred to the plateau cycle; the flexures must therefore belong still earlier in that cycle. Hence the period of the great denudation, thus far undifferentiated, should now be divided into a pre-flexure cycle, an inter-flexure-and-fault cycle, and a post-fault cycle. It is believed that a complicated scheme of this kind is much nearer the truth than the simple scheme of time division thus far postulated; but it still remains true that the post-faulting quiescent period must have been long enough for a strong excess of cliff-recession to occur in the heaved blocks, before the relatively modern erosion of the canyon was excited by a broad uplift of the region.

THE DISPLACEMENTS OF THE HIGH PLATEAUS. — Although our excursion did not lead us into the district of the High plateaus, it seems necessary to examine what has been written about them in order to see how far what has now been inferred as to the date of the faults and flexures in the Grand canyon district may find application in the adjoining district on the north. Our source of information is again chiefly in one of Dutton's reports, from which it appears in the first place that the faults of the two districts are to be considered as a single group of displacements; and, in the second place, that the uplift by which the canyon cycle was introduced probably affected the district of the High plateaus also (*a*, pp. 27, 28, 45). The faults of the plateaus are dated as younger than the youngest formations that they dislocate; namely, younger than the middle Eocene sediments and heavy lava sheets and conglomerates of a somewhat later epoch; and as old enough to have allowed a certain moderate amount of erosion since their production. The erosion on the borders of the faulted High plateau blocks seems small compared to that by which the recession of the bordering cliffs on the south has been accomplished, and Dutton therefore decides to "place the age of the principal displacements in a period which had its commencement in the latter part of Pliocene time, and extended down to an epoch which, even in a historical sense, may not be extremely ancient, and which certainly falls on this side of the glacial period" (*a*, p. 35). It seems, however, that in reaching this conclusion, no explicit consideration was given to the possibility that the faults might have occurred during a former cycle of erosion, when the district stood much lower than now; that the forms then initiated by faulting may have been much reduced or even nearly obliterated by the erosion of this earlier cycle; and that the erosion on the borders of the blocks, by which the faults have been dated, has taken place only since a general uplift has revived the erosive processes. There is some evidence that such is the case. Certain sections of the district (Dutton, *a*, Atlas, sheet 6, sections 1, 2, 3) show the Sevier plateau to consist of a heavy body of early Tertiary sedimentary strata, covered by a heavy volcanic series. This pair of rock masses ascends by an eastward rising monocline to the Fish-lake plateau, where the volcanic series has been largely removed, and even the underlying Tertiaries are reduced to much less than their normal thickness. So unequal a measure of erosion in two adjoining plateaus of similar structure suggests that the rocks of the higher one were greatly consumed during a former lower stand of the land, when the destructive processes halted at a horizon that is now found by drawing a line over the plateau tops; and that the existing valleys are chiefly the work of a revival of erosion after a broad uplift had introduced the present cycle; this broad uplift being perhaps associated with that by which the canyon cycle was introduced in the Grand canyon district. True, the displacement between the two plateaus here referred to is a flexure, not a fault; but if a former cycle of erosion is indicated by the unequal erosion on the flexed masses, it is possible that the faults which elsewhere dislocate the High plateau blocks may, as well as the flexures, have been produced in that cycle, and not in the present one. In this case, it is manifestly impossible to date the faults by the erosion that has occurred in the present cycle; they may therefore be as old in the High plateaus as in the Grand canyon district.

The relation of flexures and fractures appears to be the same in the two districts. Speaking of the High plateaus, Dutton instances three faults that are younger than the flexures which they traverse. He adds: "It is a most curious circumstance that where we find this two-period displacement the motion of the fault[1] is often reversed, — the lift of the first period is the throw of the second. It is not always so, but I believe it to be true in a majority of cases where the double movement has been detected" (*a*, p. 43). But it is of course not intended by this to imply that the High plateau flexures, which affect the Eocene beds, are as old as the Waterpocket flexure, which was eroded and unconformably buried by the Eocene (*a*, pp. 43, 44).

Origin of the Drainage System.

GENERAL EXPLANATION BY ANTECEDENCE. — Powell classified all streams as consequent, antecedent, or superimposed (now generally called superposed). In a district where superposition seemed impossible, all streams that did not follow the dip of the strata in consequent fashion were classified as antecedent. Writing of the Colorado basin, Powell said: "All the facts concerning the relation of the water-ways of this region to the mountains, hills, cañons, and cliffs, lead to the inevitable conclusion that the system of drainage was determined antecedent to the faulting, and folding, and erosion, which are observed, and antecedent, also, to the formation of the eruptive beds and cones" (*a*, p. 198). Even certain minor streams that follow monoclinal valleys along the northern flank of the Uinta mountains were for this reason explained as having been there before the mountains were raised, and the uplift of the mountains was thought to have been too slow to displace them, in spite of their small volume (*a*, pp. 159–166). To-day there can be little question that these monoclinal streams are not antecedent but subsequent; that is, they have gained their position by headward erosion along the strike of the weak strata in which their valleys are eroded — as first explained by Jukes, who wrote nearly forty years ago, "the longitudinal valleys are of subsequent origin" (p. 400) — from time to time capturing and diverting the upper courses of such consequent streams as they encountered, and thus bringing about that remarkable adjustment of streams to structures which characterizes in so high a degree all deeply denuded regions of strong deformation.

---

[1] The word "fault" is here, as in some other passages, used to include both flexure and fracture. See, for example, Dutton's account of the "east Kaibab fault" (*a*, p. 32).

Like Powell, Gilbert recognized three classes of streams, but he seems to have felt some doubt as to the generally antecedent origin of the inconsequent streams. He wrote: "A large share of the drainage of the plateaus is not consequent. How much is super-imposed and how much antecedent remains to be determined" (*b*, p. 102).

Dutton was as deeply impressed with the antecedent origin of the Colorado system as was Powell. Not only the trunk river, but most of its branches were thus explained. A consequent origin is ascribed to the lateral ravines which descend the structural slopes of the Kaibab arch (*c*, p. 195), but an antecedent origin is announced for nearly all the tributaries of the Colorado; for the San Juan, Little Colorado, and Cataract on the south (*c*, p. 219), and for the San Rafael, Curtis (*b*, p. 63), Fremont (*a*, p. 282), Paria, and Kanab on the north (*c*, p. 188), as well as for the streams that are thought to have once occupied the now dry Summit-valley depressions of the Kaibab (*c*, p. 193), and the House-rock valley between the Kaibab and Paria plateaus (*c*, p. 188).

REPLACEMENT OF ANTECEDENCE BY OTHER EXPLANATIONS. — The natural history of rivers is to-day better understood than when Powell and

Dutton maintained the antecedent origin of the Colorado drainage system, trunk and branch. It is very probable that these geologists might now modify in some degree the statements that they made thirty and twenty years ago as to the indifference of the streams, especially of the smaller streams, to the displacements of the plateau region. Other origins may be suggested for several of these waterways.

The Smaller Streams of the Grand Canyon District. — Cataract creek (called Cascade river by Newberry, pp. 62, 66, and Coanini creek by Powell, *a*, p. 197) follows in a general way the gentle northward dip of the strata that it dissects, and may well be classified as a consequent stream, revived with every uplift. A possibly consequent origin for that part of Virgin river which passes between the two parts of the Hurricane fault has been suggested above. The Little Colorado follows a monoclinal belt of relatively weak Permian and lower Triassic strata for a hundred miles, and in this part of its course it may be plausibly regarded as a subsequent stream; such was certainly its habit where we crossed it in the Permian belt on the Flagstaff-Tuba road; but for forty miles northwest from this point to its junction with the larger river, it runs obliquely against the gentle structural slope of the Marble platform and enters the main canyon just east of the Kaibab monoclines, a highly significant fact which will be referred to further on. Paria creek has, according to the geological maps of the district (Dutton, *c*, Atlas, sheets II., XXI., XXII.), an anticlinal course in its upper, and a monoclinal course in its lower part. Although the lower part is now deeply incised in resistant Triassic strata on the northeast border of the Paria plateau, its position there may have been gained by headward growth along the once-overlying weak strata of the gently dipping monocline during a lower stand of the land; for the stream seems to be accordant with the strike of the beds. The upper part of the Paria drains the denuded district in which the Kaibab arch fades away to the north (Dutton, *a*, pp. 253, 297); the lateral branches of the stream are here to all appearances normal obsequent streams, whose length increased as the denuded area widened; the trunk stream is merely the axial member of the obsequent group, longer than the laterals because the dip of the strata to the north is gentler than to the east and west. The whole length of the creek may therefore be reasonably explained as an example of spontaneous adjustment of drainage to structure, and not as of antecedent origin. House-rock valley is unquestionably subsequent, as has been implied already on page 124, and as will be more fully considered below. Kanab creek has every appearance of being an obsequent stream, of unusual length, it is true, but associated with receding cliffs of unusual number and strength, in a region of extraordinary denudation. The growth of this creek and its branches, like that of the Paria headwaters, must have been at the expense of many pre-existent consequent streams. The essential principles of the development of such streams were stated by Powell in a general way. He said, speaking of a series of receding cliffs, facing southward: "As the cliffs are undermined, . . . the area with a southern drainage would be increased, the area with a northern drainage correspondingly diminished" (*a*, p. 210). Extensive changes of this kind must have gone on during the great denudation of the plateau cycle, and the growth of long obsequent streams is a natural, almost a necessary accompaniment of the great recession of the cliffs that flank the High plateaus on the south.

The Streams of the San Rafael Swell. — Curtis creek and San Rafael river were not within our field of observation, but they gain importance from having been described as typical antecedent streams by Dutton, who thus explained them because they run across the San Rafael swell without regard to its structure (*b*, p. 63). They may, however, be equally well regarded as superposed through overlying Tertiary strata which may have once covered the denuded swell unconformably. They would thus be associated with a part of Fremont river — called Dirty devil river by Powell (*a*, p. 67), and Gilbert (*a*, p. 130, Plate I.), — which Dutton explains as having been superposed on the mesozoic strata of the Waterpocket flexure (*a*, p. 288), although regarding it as antecedent in its original course on the Eocene (*a*, p. 282). It has already been pointed out that the swell and the flexure are neighboring structures, involving the same series of strata. Dutton demonstrates that the flexure is of pre-Tertiary date (*a*, p. 288, *c*, p. 215), and Gilbert comes to the same conclusion (*c*, pp. 10–12); for Cretaceous strata are involved, and their bevelled surface is unconformably covered by the horizontal Eocene. It is eminently possible, as has already been suggested, that the swell is of the same date, and that its truncated uplift was buried by the Tertiary strata, which certainly once stretched over it. Either superposition or antecedence would locate the two streams on the swell without regard to its structure; but of these two processes the latter seems to me much the less probable for the reason that, if the whole series of strata had been domed, and if the antecedent streams had had to cut down through the successive alternations of strong and weak strata from Tertiary to Carboniferous, a greater amount of adjustment to weak structures than is now seen would have been almost inevitable. This opinion is fortified when it is noted that the two streams in question are of moderate size, and still more when it is seen that they head to the northwest against the retreating Tertiary escarpment, thus suggesting that they are now longer and larger than they were formerly. Their antecedent origin seems improbable, to say the least.

The Summit Valleys of the Kaibab. — The irregular longitudinal depressions, including Summit valley and De Motte park, in the highlands of the Kaibab plateau, have been regarded as of especially obscure origin. Dutton thought them all as the work of a single south-flowing antecedent stream whose waters had been withdrawn in the change from the moist Miocene to the dry Pliocene climate, and whose bed had been deformed by the local uplift of the Kaibab (*c*, pp. 193–195). This view seems open to question because of certain improbabilities that it involves and of certain possibilities that it omits. The association of the Summit valley depression with the axis of the Kaibab uplift, a broad flat arch, with stronger flexure on the east than on the west, seems too close to be the work of chance, — as would necessarily be the case if the depression were the work of a stream whose origin antedated the uplift. The axial line of the longitudinal depression does not now descend continuously towards the canyon; a long northern stretch (Summit valley proper) slopes northward and discharges to the east into House-rock valley and thence to Paria river; a more southern portion (De Motte park) also slopes northward, and, except for shallow sinks on its floor, discharges eastward by a deep ravine down the east Kaibab monoclines. Two other shorter portions also slope northward. Certain intermediate parts slope southward, but they are much shorter than the parts just mentioned. Dutton concludes that all these parts once had a continuous southward slope, and that the present discontinuity of slope is due to a reversal of grade by the uplift of the Kaibab.

The continuous southward slope assumed for the depression seems open to question, especially when it is remembered that the recession of the Triassic cliffs demands a more remote date for the Kaibab arch than early Pliocene. The retreat of the heavy Triassic strata around the north end of the Kaibab suggests that at least some of the mesozoic strata once stretched partly over the uplifted area: they may indeed have stretched all over the Kaibab when the uplift was formed, as suggested by Walcott on account of the absence of fractures in the east

Kaibab flexure, as has already been indicated. If so, there should have been a time in the denudation of the uplifted strata when their lateral slopes were deeply gashed by consequent streams; and when subsequent longitudinal branches of these streams were developed in anticlinal valleys, opened north and south from the head of each consequent stream on the weak Permian and lower Triassic beds that were discovered along the axis of the uplift. The longitudinal valleys would be then enclosed by the retreating escarpments of the Triassic sandstones on the east and west; the Jura mountains of to-day offer many examples of this kind. In the early stages of this development there would be many separate anticlinal valleys along the axis of the uplift, each drained by its own outflowing consequent stream; but as time went on, the branches of the deeper-cut consequents would capture the anticlinal drainage area of the shallower-cut consequents, and as the axis of the uplift descends to the north, these captures would generally be made in a southward direction; thus the drainage areas of the successful consequents would become unsymmetrical; each one would receive a longer anticlinal branch from the south than from the north. As between east and west flowing consequents, the former would generally be more successful than the latter, because the eastern slope of the Kaibab descends to a much lower level than the western; the difference of altitude of corresponding strata in the Kanab plateau and the Marble platform being nearly two thousand feet (Dutton, *c*, Plate II.). If the rule regarding the earlier date of flexures than of faults prevailed here as well as elsewhere, the eastern descent from the Kaibab during the pre-faulting period would have been three thousand feet or more in excess of the western descent; and all the anticlinal valleys would thus come to discharge eastward from near their northern ends, as in Figure 12.

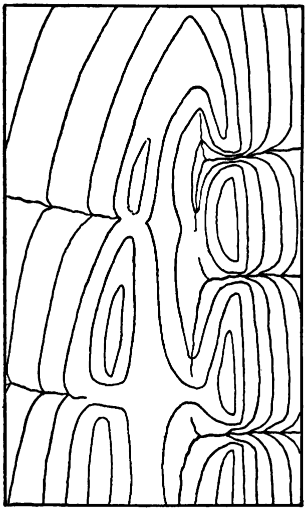


FIGURE 12.
Diagram of self-adjusted drainage on the Kaibab.

The more important of the longitudinal streams thus established on the Kaibab might have worn down their channels into the resistant Aubrey strata before the Triassic sandstones had retreated so far on the east and west as to allow their infacing escarpments to shed water into the lateral subsequent valleys opened on weak monoclinal strata along the flanks of the uplift. But when a sufficient retreat of the Trias had been accomplished and the lateral subsequents had been developed, the axial or anticlinal streams would be reduced to small volume; for much of the drainage of the uplift that used to enter them will at this later stage flow away from them down the stripped structural slopes on either side. The drainage of the stripped slopes forms a new series of lateral waterways; they are not strictly consequent streams which have persisted since the Kaibab was uplifted, but are regenerated successors of the original consequents. It may be noted that the valleys of such regenerated consequent streams will have been eroded first in their upper parts and afterwards in their lower parts, thus reversing the usual order of progress in which erosion acts in a more retrogressive fashion.

The topographical maps of the Kaibab (Dutton, *c*, Atlas, sheets XXI., XXII.) allow us to compare these deduced conditions with the facts. The lateral subsequent valleys have now shifted to the lower ground bordering the Kaibab, by reason of the far and wide retreat of the Trias; the most representative example being House-rock valley, well enclosed by the Trias of the Paria plateau which still stands near the Kaibab on account of the relatively low level of the Marble platform. The regenerated consequents have scored the flanks of the plateau with deep ravines. Four axial valleys all discharge eastward from near their northern ends. Near the northern termination of the Kaibab Carboniferous area, there is a canyon that cuts directly across the uplift, draining a portion of the western Permian monoclinal valley to the corresponding eastern monoclinal valley (House-rock valley) at Adairville; this probably being an example of structural superposition, that is, of a stream whose course was determined when the weak overlying Permian strata still covered the area during the plateau cycle and whose course has been maintained through the resistant Carboniferous strata. The only exception to the rule of eastern discharge is in the case of the southern end of De Motte valley; but this lies beyond the area of greatest altitude on the Kaibab (nine thousand feet) and discharges, as might have been expected, southward to the canyon. It is therefore not necessary to conclude that the "Summit valley" depressions of the Kaibab were ever drained by a single antecedent stream, and it seems advisable to regard the Kaibab uplift as having taken place long before the mesozoic strata were stripped from its crown; thus the evidence from drainage confirms that derived from structure and erosion.

THE ORIGIN OF THE COLORADO IN THE GRAND CANYON DISTRICT. — In view of the various origins other than antecedent that may be ascribed to the branches of the Colorado in the Grand canyon district, it does not seem legitimate to adduce these streams in support of the antecedent origin of the trunk river. That question must be settled by itself, and it is by no means free from difficulty. The antecedent origin of Green river in its passage through the Uinta mountains has been seriously impugned by Emmons (1877), who maintains that it is a superposed river (*a*, pp. 194, 205; *b*). The antecedent origin of certain parts of the Colorado in the Grand canyon district has later been questioned by Jefferson (1897), who points out the southward bends of the river around the Kaibab and Shivwits plateaus, and suggests that these deflections may be consequent on local uplifts instead of regardless of them. To these doubts must be added a whole series of considerations which had no place in the discussions of Powell and Dutton regarding the spontaneous rearrangement of watercourses during the dissection of a region which has suffered repeated movements and heavy denudation. It is true that, as the Colorado runs for the most part on nearly horizontal strata and in a general way transverse to the displacements that its basin has suffered, it cannot be classed with subsequent rivers, for they always follow the strike of a weak stratum in a series of tilted rocks. But the studies of Hayes and Campbell on the migration of certain divides in a region of nearly horizontal strata that has repeatedly suffered slight tilting during the development of its rivers deserve serious consideration in the plateau province, where they have as yet found no exponent. Until this new aspect of the problem shall have been discussed by some one who has a wide acquaintance with the region, it does not seem safe to regard even the trenchant Colorado in its course through the Grand canyon as a purely antecedent river.

In the mean time I cannot resist the temptation of speculating somewhat freely as to the possible development of the great river across the Grand canyon district, especially in view of what has been said in previous sections as to the successive movements that the region has suffered, and in view of the many ways in which drainage lines may be modified during and after such movements. Certain considerations that I wish to bring forward in this connection concern not only the Grand canyon district, but also the adjacent district of the High plateaus and the province of the Basin ranges (or the Great basin) which have not come especially under my observation. In referring to these areas under the names of the Grand canyon district, the High plateau district (these two together making a large part of the Plateau province), and the Great basin province, it must be understood that the existing topographical features are of relatively modern origin, that altogether different topographies prevailed in earlier periods, and hence that the names here used will serve chiefly to designate areas and not forms. The Great basin province was for a time a lofty mountain region; the Grand canyon district was a district of broad plateaus; and the High plateaus were part of a great interior basin. Most of the statements concerning these districts are, it is believed, well assured, but some of them are open to the serious criticism of departing from the conclusions reached by the original observers whose observations are quoted. This section as a whole must therefore be largely speculative; yet the speculations have some recommendation, in that they do not contradict recorded observations, and that they combine to form a mutually consistent scheme of geological events. These speculations may at least serve as targets toward which discussion may be aimed, even if they do not present any ultimate truth.

The Geological History of the Region. — The Basin range province has been disturbed by post-Jurassic plication and by late Tertiary faulting. King wrote that the Great basin "was a region of enormous and complicated folds, riven in later time by a vast series of vertical displacements. . . . The Great basin . . . has suffered two different types of dynamic action: one, in which the chief factor evidently was tangential compression, which resulted in contraction and plication, presumably in post-Jurassic time; the other of strictly vertical action, presumably within the Tertiary" (pp. 735, 744). Dutton makes a similar statement: "These [Basin range] flexures are not . . . associated with the building of the existing mountains. . . . The flexures are in the main older than the mountains, and the mountains were blocked out by faults from a platform which had been plicated long before, and after the inequalities due to such pre-existing flexures had been nearly obliterated by erosion" (*a*, p. 47). Several passages in Gilbert's first western report are of interest in this connection. He concluded "that the Plateau [region] is not a unit in history and origin, and that the only criterion by which it can be distinguished from the [Basin] range country, is the . . . superficial one of table and ridge. . . . The whole phenomena [of displacement] belong to one great system of mountain formation, of which the ranges exemplify advanced, and the plateau faults the initial, stages." He goes on to say that the Basin range province was disturbed at the close of the Jurassic and of the Eocene periods; while the faults in the plateau province are of Tertiary date. In the border land between the two provinces, the later disturbances not merely run parallel to the Jurassic upheavals, but in places actually coincide with them (*a*, pp. 58, 59, 61).

The Effect of the Flexures. — During the earlier elevation and denudation of the Basin ranges, in post-Jurassic times, much waste seems to have been carried from them towards the east and northeast. While the Cretaceous strata of Utah and Arizona are marine deposits, the Tertiaries are continental; and from this it may be inferred that the movements of the Cretaceous-Tertiary interval (such as the Water-pocket flexure) formed enclosed basins, from which the sea was excluded, and into which the waste was gathered as lacustrine or fluviatile deposits. The great volume of the successive Tertiary formations implies that the highlands of the southwest long maintained a considerable altitude. It is possible that their height was intermittently renewed by movements which gave rise, in the Grand canyon district, to the monoclinal flexures; for these flexures had, as has been shown, prevailingly an uplift on the west or southwest. It is postulated that the initial effect of a series of flexures would be to form a flight of very broad steps, such as certainly must have been the case with two well-defined members of the series, the east Kaibab and the Echo flexures; but as the surface of each "tread" may have departed from a level attitude, it is not safe to assert that the height of the top of the flight (southwest) above the bottom (northeast) was equal to the sum of all the "rises." It is, however, here assumed that the top was higher than the bottom, and that the flexures were effective re-enforcements of the mountain-making upheavals in maintaining the Basin range province at such an altitude that it could shed waste abundantly to the northeast. In this connection, it should be noted that the Aubrey cliffs on the south of the plateaus are determined by a north (northeast?) dipping flexure (Gilbert, *a*, p. 46, section), and that the east-dipping strata which are now found close along the fault lines by which the Basin ranges are separated from the plateaus, show some of the strongest dips of the region.

Through all the time during which the mountains of the Basin range province stood higher than the plateau area, the lines of river-flow may be assumed to have followed the direction in which the mountain waste was so abundantly transported; namely, east and northeast; and through the second chapter of this time, after the later flexures had been formed (the inter-flexure-and-fault cycle), the destructive processes which had previously denuded only the mountains of the Basin range province are believed to have extended to the Grand canyon district also; but deposition still continued in the northeast, interrupted only by minor unconformities. The northward retreat of the great escarpments by which the High plateaus are now bordered on the south, must have then begun; the retreat was probably greater on the southwest, where the stepping flexures are supposed to have caused the greatest renewals of uplift. At the close of the cycle that began with flexing and ended with faulting, the Triassic escarpment, for example, may have receded to a line that is roughly marked by three points: the lava mesa on the Shivwits plateau, the junction of the Great and the Little Colorados, and the eastern side of the lava fields around Mt. San Francisco; but something of a northward bend must be made in this line as it crosses the flat arch of the Kaibab. The amount of denudation accomplished during this cycle is indeterminable; yet if any are disposed to limit it to a small measure, their attention should be called to the local instances of great erosion in the Cretaceous-Tertiary interval, when the Waterpocket flexure was essentially baselevelled. As complete a consumption of the up-flexed blocks in the southwest may have been accomplished before faulting took place, although no unconformities remain there to prove it. But although the denuded southwestern area from which the Trias had been stripped may have been reduced to moderate relief, it need not have been a lowland with altitude but little above sea-level, for its streams discharged into interior continental basins, very probably without outlet, on whose floors the Tertiary sediments were accumulating. Some of these basins may have held lakes, intermittently at least; but the occurrence of mountain ranges for hundreds of miles to windward (west and southwest) must have tended to produce a dry climate in the lower continental area to leeward; many of the basins may have been nearly or quite dry, gathering (as I have elsewhere pointed out (*b*)) fluviatile rather than lacustrine deposits at considerable altitudes above the sea.

The Effect of the Faults. — The faulting of the region is the next important occurrence. The faults have their uplift in nearly all cases on the east; hence the eastern area, from having long served as a seat of deposition, became in turn the seat of extensive denudation. At the same time, the western area was greatly depressed from its long residence at a high mountainous altitude. It is not desired to assert that all the faulting of the Basin ranges occurred at the time when their province was dropped to a less altitude than that of the plateaus by the production of great faults along the boundary of the two provinces; the faulting of the ranges was probably a complicated process, but on the whole it is believed to be associated with the lowering of the Basin range province, rather than with the earlier stage of its general elevation. It may be noted that in the southwest (southeastern California) some of the Basin range blocks have been greatly worn away (Fairbanks, p. 70), while in the northwest (southern Oregon) some of the blocks are as yet very little eroded (Russell, *a*, p. 444). In general, however, the post-faulting erosion of the ranges has produced a mature dissection without altogether destroying the block outlines (Powell, *b*, p. 198; Gilbert, *d*, p. 341). The most recent studies of the ranges by Spurr, reported at a recent meeting of the Geological Society of America, indicate that the faulting has been more complicated and longer continued than had formerly been supposed. In certain cases, streams flow through instead of around the ranges of to-day, from which it may be inferred that at least some of the existing drainage of the province had been established before the range blocks were tilted up.

The drainage consequent on the new topography produced by faulting is assumed to have taken the best course that it could find to the southwest. The chief discharge may have here and there followed preexistent valleys, but with a reversed direction of flow (see extract from Powell, below). Many short-lived lakes may have been formed by the somewhat adverse eastward tilting that has been supposed to have accompanied the faulting of the blocks; but there does not appear to be any positive proof that the tilting may not have been produced at the earlier time of flexing instead of at the later time of faulting; certainly the strata of the Marble platform dip gently eastward between the east Kaibab and the Echo flexures, and here the dip and the flexures seem to be of the same date. In any case, the drainage of a large area of northeastern country, floored with Cretaceous and Tertiary strata, seems to have been gathered at a favorable point of discharge; namely, near the point where the Kaibab uplift had been greatest, and where the exposure of the weak Permian beds had caused the greatest break in the strong Triassic escarpment by which the interior country was enclosed. Westward from the Kaibab, the escaping drainage presumably followed the lowest line that it could find between the Triassic escarpment on the north and the general ascent of the stripped Carboniferous country to the south. Perhaps in some such manner the Colorado found its way across the Grand canyon district to the broken-down mountains of the Basin range province, and thence southwestward to the sea. The river would thus seem to have been for the most part consequent on the form and slope of the surface at the time of faulting, yet it may have been antecedent to various subordinate movements of the crust here and there; and there is a possibility that it may have been in some greater or less degree developed after the faulting by the retrogressive erosion of west-flowing streams that had been encouraged by a favorable tilting of their courses. McGee has suggested the latter process to explain certain streams in "Papagueria" (Arizona and Sonora), whose growth is thought to have been thus accelerated during a time corresponding to what is here called the canyon cycle (*c*, p. 352), and this process certainly deserves deliberate consideration.

It should be pointed out that a consequent origin for the Colorado is indicated by the following passage in Powell's report on the Uinta mountains: "At last the movements which began at the commencement of Tertiary time succeeded in bringing the whole [Plateau] area not only above the level of the sea, but above the general level of the Basin province itself; so that while the Basin province was drained into the Plateau province in earlier Tertiary time, in late Tertiary time the drainage was reversed, and the streams of the Plateau province found their way to the sea by passing through the Basin province. . . . It is the opinion of Mr. Howell, and I believe also that of Captain Dutton, that this drainage was in some cases reversed along the very channels occupied by the ancient streams which ran from the Basin province into the Plateau lakes" (*b*, p. 35). There is in this quotation much more suggestion of a consequent origin of the Colorado than is elsewhere to be found in the reports of the observers whose names have been so often cited here: nevertheless, the published reports give no indication of the manner in which the denudation of the upflexed area on the southwest may have prepared the way for the production of a southwestward slope when the district was afterwards broken and heaved by faulting.

If there be any truth in the suggestion that the Colorado did not cross the Grand canyon district until after the faulting of the plateau blocks, then it was in the cycle of erosion thus initiated (the post-faulting cycle) that the great denudation was essentially completed, leaving little more than the stripping of weak strata and the canyon-cutting for the canyon cycle. The retreat of the escarpments on the faulted blocks during the last chapter of the great denudation must have been over a considerable distance, for each line of cliffs should have been, before the faults were made, worn back further on the west of a flexure than on the east; while now, in consequence of the faults, the reverse relation has been brought about. The total recession since faulting has therefore probably been decidedly greater than the distance by which the cliffs on the east of a fault-line now stand north of their fellows on the west; and thus an even greater antiquity for the faults is suggested than has been thus far suspected.

The Bends of the Grand Canyon. — There are three peculiar features in the course of the Grand canyon: one is the southward bend around the Kaibab, the second is a northward bend toward the mouth of Kanab creek, and the third is a southward bend around the Shivwits plateau. Jefferson has suggested that the first and third of these bends may be consequent on the form of the surface given by the flexures; but according to the analysis of events here presented, the drainage consequent on the flexures ran to the east and northeast, and the westward course of the Colorado was not assumed until after the flexed plateaus had been greatly denuded, and until the denuded surface had been raised on the east by the block faulting. Something later than the initial slopes of the flexed surface should therefore be found to guide the river, if an antecedent or initially consequent origin is not accepted for it. It has seemed to me that certain details in the flexing of the Kaibab and Coconino plateaus may here be appealed to.

The eastern lobe of the Coconino is a striking feature as seen from the lower plateau on the south (Figure 13) and from the valley of the Little Colorado on the east. The surface of the district at the time of flexure was presumably covered by some of the mesozoic formations. Just before the time of faulting, the Trias may have been pushed back to some such outline as would reveal the Permian in the valleys on the south and west of the Kaibab, and perhaps even some of the Aubrey was laid bare on the highest part of the Kaibab. Up to this time, the drainage hereabouts was eastward down the slopes of the Kaibab and Echo flexures, but many longitudinal subsequent streams must have been developed along the weak lower Triassic and Permian strata west of and underlying the Triassic escarpment that was then retreating eastward towards its present position on the axis of the Echo flexure. Now as the drainage of the interior basins of the northeast was turned southwestward by the upheavals associated with the faulting — long after the close of the Eocene — the most available point for its escape was, as has been stated, near the centre of greatest local upheaval (the Kaibab) where the revelation of weak underlying strata had reduced the level of the Trias by sapping, and had thus produced an amphitheatre, open on the southwest. At the same time, the subsequents under the Triassic escarpment were gathered into a single stream to form the Little Colorado, discharging northward; but this result may have been in part the effect of spontaneous interaction among the streams themselves, after their habit in such cases, and only in part the effect of upheaval at the time of faulting. Once reaching the Kaibab amphitheatre, the new-born river followed southward along the subsequent Permian valley which must have been opened along the east Kaibab flexure, until the slopes of the northeast-dipping flexure that limits the Coconino plateau were encountered. The river then turned northwestward along a trough of weak and low-lying Permian strata that occupied a depression between the two uplifts; and it is notable that the small but sharp flexure which bounded this trough on the south may now be traced through the spurs of Carboniferous strata on the southern canyon wall (Dutton, *c*, p. 185). The flexure comes from the southeast, where it forms the northern border of the eastern lobe of the Coconino plateau; it trends northwest, as if to join the now-faulted flexure at the western base of the Kaibab. We had a good view of it from the southern rim and from the bottom of a side canyon. Thus interpreted, it appears that a part of the true Kaibab uplift lies south of the canyon, where it slopes into what is locally known as "the

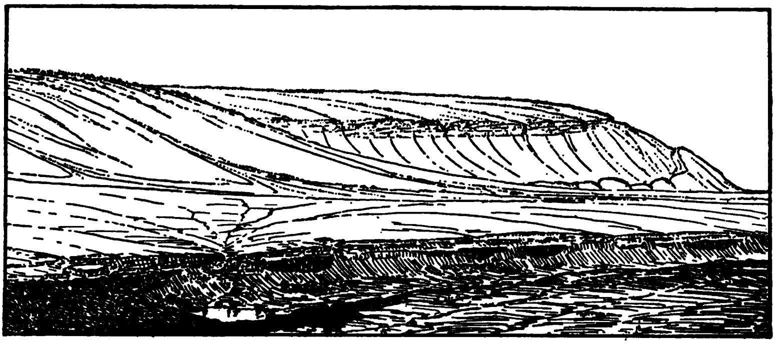


FIGURE 13.

The eastern lobe of the Coconino plateau, as seen from near Lockett's tank. The foreground shows a ravine in the upper Aubrey limestone, once filled with lava, and now partly re-excavated. The "tank" is a waterfall pool. Drawn from rough sketch.

Basin," and ends on reaching the strong flexure by which the strata are turned up into the Coconino; but it is probable that in so far as the terms Kaibab and Coconino have a geographical application, their areas will be separated by the canyon rather than by the flexure that separates their uplifts.

The further northwestward course of the river may have been made inviting if a relative depression or failure of uplift occurred in the eastern Kanab plateau when the west Kaibab faults were formed, and Dutton gives some evidence that this was the case when he describes the northward slope of the Kanab along the southwest border of the Kaibab (*c*, p. 184); but I am at loss to find any conclusive proof of such a condition, apart from the behavior of the river itself. The south bend on the Shivwits may plausibly be explained as a displacement from a once more direct course by reason of the volcanic outpourings which now culminate in Mt. Dellenbaugh.

Speculative Character of the Preceding Sections. — All this is avowedly speculative; and it is presented rather as a combination of various possibilities than as embodying the only permissible explanation for the course of the Colorado. Other stages of the great denudation, now unsuspected, may yet be discovered in the development of the Grand canyon district; new processes of river development, as imperfectly known to-day as was the growth of subsequent streams at the time of the earlier exploration of the canyon, may be added to the growing resources of physiographic study; and all of these elaborate stages and processes will deserve as careful consideration as has been given to the simpler conception of the antecedent river, marked out by the deeper lines of the Eocene lake floor, and remaining unaltered, save for deepening, ever since the ancient lake became dry land.

Nothing less than extended studies over a large area of the Cordilleran region will suffice to determine what value should be given to the various possibilities thus suggested. It is not my intention to discount such studies by attempting to announce their result at once; but only to emphasize the opinion that the facts now on record, combined with such knowledge of the region as our party was able to gather last summer, warrant the consideration of at least one hypothesis alternative to the theory of antecedence, as an explanation for the origin of the drainage lines in the Grand canyon district. I do not on the one hand consider the antecedent origin of the Colorado disproved, but, on the other hand, such an origin does not seem compulsory. The chief objection to the theory of antecedence is not that rivers cannot saw their way through rising mountains, for there are some well-attested examples of such a process, in which its successive steps are more or less fully traced; but rather that this theory makes a single stride from the beginning to the end of a long and complicated series of movements and erosions, overlooking all the opportunities for drainage modifications on the way. The simplicity of the theory is certainly attractive in comparison with the rather tedious length of the considerations that are involved in the attempt to analyze the processes of spontaneous river adjustments; but it should now be generally recognized that nothing less than a deliberate analysis of all movements (of which the uplift of the present plateaus is the last) and erosions (of which the cutting of the Grand canyon is the least) will suffice to discover the actual origin of the Colorado. The preceding paragraphs are offered as the beginnings of such an analysis.

The Erosion of the Grand Canyon.

THE CANYON CYCLE. — The general uplift that introduced the canyon cycle in the Grand canyon district seems to have been accompanied by a strong renewal of movement on the faults that divide the Basin range province from the plateaus. The northward increase in the heave of the bounding faults between the Basin range province and the plateaus suggests that the uplift of the High plateaus at this time was greater than that of the Grand canyon district. Dutton says: "Until near the close of the Pliocene the High plateaus were not only the theatre of an extended vulcanism, but those portions which never were sheeted over by lavas were low-lying areas, where alluvial strata tended to accumulate. They remained, in fact, base levels of erosion during the greater part of Tertiary time" (*a*, p. 23). It is possible that some movement was renewed on other than the bounding fault-lines at the time of the general uplift, but it has been pointed out above that there is good reason for thinking such movement to have been insignificant on the fault line near Pipe spring. Still, in the south Toroweap valley (Dutton, *c*, p. 94), in the Great Basin (Gilbert, *d*, p. 341), and in the High plateaus (Dutton, *a*, pp. 250, 277), there are various indications of faulting at a much later date than the beginning of the canyon cycle.

Comparison of Glen and Marble Canyons. — Chief among the foregoing considerations that point to the division of the Tertiary history of the Grand canyon district into at least two cycles of erosion is the similar resistance to weathering manifested by the Triassic and the

Carboniferous strata. It would be difficult to determine by ordinary tests which one of these two formations is the more resistant, so strong does each appear; but a very good natural test of their relative strength is found in a comparison of the upper part of Marble canyon, cut in the upper Carboniferous, with Glen canyon, cut in the Triassic rocks themselves, where they descend to the level of the lower plateaus east of the Paria-Echo monocline. The two canyons are of similar date, for the monoclinal flexure that separates them is much older than either canyon; they are of similar width (Dutton, *c*, Atlas, sheet XXII.); and hence the resistance of their walls must be similar. It is true that the widening of Glen canyon has been retarded by the failure of the river as yet to cut down to the weak blue clays that underlie the heavy red sandstones of the Trias; while the stripping of the Trias from the great area of the plateaus south of the Grand canyon, and the recession of the Vermilion cliffs for fifty miles or more north of the canyon have been greatly aided by the sapping of the underlying clays; but even with this aid it does not seem possible to explain the great denudation of the plateaus in contrast to the narrowness of the canyon by a single cycle of erosion.

Stage of Development of the Canyon. — The day has passed when it was necessary to ask whether the canyon is the work of the river; but in the renewed attention lately given to the relation of trunk and branch valleys, certain features of the canyon serve as important witnesses. In spite of the youth of the canyon, its branch streams generally enter at accordant grade with the main river, and thus testify to the promptness with which side valleys are cut down to the depth of the main valley at their points of junction. This feature must be considered in some detail.

Rapids in the Canyon. — The canyon is so young that the great river at its bottom has not yet established a completely graded channel. True, there are no leaping waterfalls now remaining: "Throughout the cañons there are no cataracts; that is to say, at no place does the river fall from a ledge of rock into the pool below" (Gilbert, *a*, p. 75). But there are still many rapids, especially in those parts of the canyon where the fundamental crystallines are trenched. When these resistant ledges are rasped away, the upper canyon will be significantly deeper than it is now. On the other hand, the corrasion of the canyon must at present be proceeding at a slower rate than at some earlier time, before the development of the graded stretches that now constitute the greatest part of the river. It was the existence of these graded stretches, where the river is hardly more than a transporting and comminuting agent, that brought Powell's boat journey within the limits of possibility, even while the lingering rapids made it terribly dangerous. The occurrence of rapids on the down-stream side of boulder heaps that have been washed into the main canyon by the flooded streams of side chasms, also indicates a retarded rate of corrasion by the main river. Powell mentions several such obstructions (*a*, pp. 82, 83, 97); Gilbert gives a more explicit account of them and points out their probably temporary character. He says that many of the tributary canyons "are of very rapid fall, and are occasionally traversed by powerful torrents, which sweep down bowlders of great size — in some instances 10 or 15 feet in diameter — and heap them in the main cañon in dams, that must often be of great depth. Over each of these the water finds passage at the edge opposite the tributary, and descends the lower slope with swift current and broken surface; and thus arise the great majority of the rapids." It is further pointed out that there are times "when each of these dams in turn is removed . . . so that, while the dams will recur at the same localities and with the same characters, they cannot be regarded as strictly permanent" (*a*, p. 71; see also Dutton, *c*, p. 241).

It may therefore be concluded that although the canyon is still to be deepened, the river as a whole approaches and for considerable parts of its course actually reaches the delicate balance between degradation and aggradation which characterizes a maturely graded stream. After such a condition is reached, further deepening of a valley is possible only with the decrease of the load furnished to the main stream by its side streams, in the later maturity of the region.

Junction of Trunk and Branch Streams. — It is now to be determined how the side streams join the main river at this relatively early stage in the present cycle of the Colorado. The importance of this question turns on the prevailingly discordant junction of side and main valleys in strongly glaciated mountains, as has recently been pointed out by De Lapparent and Richter for the fiords of Norway, by Gannett for Lake Chelan in the Cascade range, and by Penck for the valleys of the Alps. I have lately prepared a general review of this problem in connection with my own observations on the valley of the Ticino in southern Switzerland and elsewhere in Europe (*c*, p. 310; *d*, p. 138). It has been contended by some that the discordant junction of side and main valleys in the Alps is the normal result of the more rapid deepening of the main valley by its larger stream, even to the point of thus accounting for lateral valleys standing five hundred or more feet over main valleys whose flood plains are ten or twenty times as broad as their rivers. On the other hand, the observers above named conclude that the discordance is due to glacial erosion. If the former view were correct, then surely the discordance of side and main valleys ought to be very strong in the Grand canyon, where there is no question of glacial erosion, where the disparity of volume between trunk river and side streams is notoriously great, and where the main valley is still so young that no significant widening of its floor has been yet accomplished. Yet singularly enough, the side canyons of the Colorado join the main canyon at accordant levels in nearly all cases. The views from the southern rim of the canyon at various points near Hance's and Cameron and Berry's, and still better from the great Red-wall spur that advances northward from the "copper mine" on the Grand view trail, show repeated instances of dry or nearly dry lateral canyons, only five or six miles long, which are nevertheless cut down at their mouths as deep as the main river, if their lower course lies on the stratified rocks. It is only where the main canyon narrows on entering the resistant crystallines that the side canyons are held up at a discordant level; and even there the large lateral canyons seem to enter closely at grade (see detailed map, by Bodfish, Dutton, *c*, p. 258, Plate XLII.). However discordant the side and the main canyons may have been during a still earlier stage of the present cycle of erosion, Playfair's law is already exemplified to-day; and if, under conditions of peculiar difficulty, some of the smaller streams have not yet reached a normal relation to the master stream, they only prove the verity of the law by the need of their being excepted from it.

As my own views of the canyon were only in the middle of the Kaibab section and from Vulcan's throne in the Toroweap, the following references to records made by others may prove pertinent in this connection. Powell describes his ascent of a side canyon west of the Kaibab, and mentions waterfalls in its course, one of which was one hundred and fifty feet high; but as no fall is mentioned at the mouth of the side canyon, it probably unites with its master in accordant fashion (*a*, p. 92). A little further down the main canyon, a stream from the north leaps into the river "by a direct fall of more than a hundred feet" over a "bed of very hard rock, . . . thirty or forty feet in thickness" (*a*, p. 93). Before reaching the crystallines of the Shivwits canyon, "a little stream, with a narrow flood plain, comes down through a side cañon" from the north. An Indian settlement was found there, with fields of corn and squash (*a*, p. 96). Even within the crystallines of the Shivwits block, small side streams of "gentle slope" are reported by Wheeler as entering the main river and forming boulder rapids, but no mention is made of falls at the stream mouths (pp. 166, 167). Plate XVII., in Dutton's Monograph, reproduced from a photograph, shows two side canyons entering the narrow inner gorge of the main canyon just east of the Toroweap, and joining the main river in accordant fashion. Evidently, then, hanging valleys have no important place in the Grand canyon; and the hanging lateral valleys of the Alps, whose floors are five hundred feet or more above the open flood plains of their main valleys cannot be explained by normal river erosion.

Some striking examples of hanging valleys in a very narrow canyon are, however, described by Gilbert in the case of the North fork of Virgin river in southern Utah, where it cuts through the massive Triassic sandstones. This narrow defile is many times deeper than broad; its walls are nearly vertical and parallel for the greater part of their height, but they depart sufficiently from the vertical, now to this side, now to that, to hide the sky from the adventurous observer who follows the narrow, boulder-strewn stream bed. "The side cañons all partake of the character of the main, but, being worn by smaller streams, are narrower, and their bottoms are of steeper grade. Many of them at their mouths are not cut so deep as the one we followed, and discharge at various heights above the river" (*a*, p. 79). Gilbert's figure of this canyon has become well known from being copied on the binding of Leconte's "Elements of Geology," as if in witness of the efficiency of erosive processes; but it may be noted that a plain of denudation, truncating the edges of upturned strata, is a much more impressive though less outspoken witness to this conclusion.

THE GEOLOGICAL SECTION IN THE CANYON WALL. — The excavation of the Grand canyon is properly regarded as a colossal work. Standing on the southern rim, the view of the chasm is overwhelming; yet the prospect includes four other records of erosion, and suggests two more still, in comparison with any one of which the excavation of the canyon is but a small matter. This has all been pointed out by Powell and others; but it deserves repeated statement.

The geological section exposed in the northern side of the canyon in the Kaibab, as seen from any of the promontories in the neighborhood of Cameron and Berry's or Hance's hotels, includes the fundamental crystallines, the inclined strata of the Grand canyon series (Algonkian), twelve thousand feet thick, and the palæozoic series, over four thousand feet thick.

The strata of the Grand canyon series are seen in the form of a wedge with its apex pointing westward, as in Figure 14; its lower members rest unconformably on an inclined floor of denuded schists, while the basal members of the palæozoic series rest unconformably on a horizontal floor denuded on the schists continuously with the bevelled upper surface of the wedge of the Grand canyon series.[1] The skyline of the Kaibab is, as has been pointed out above, the edge of a stripped struc-

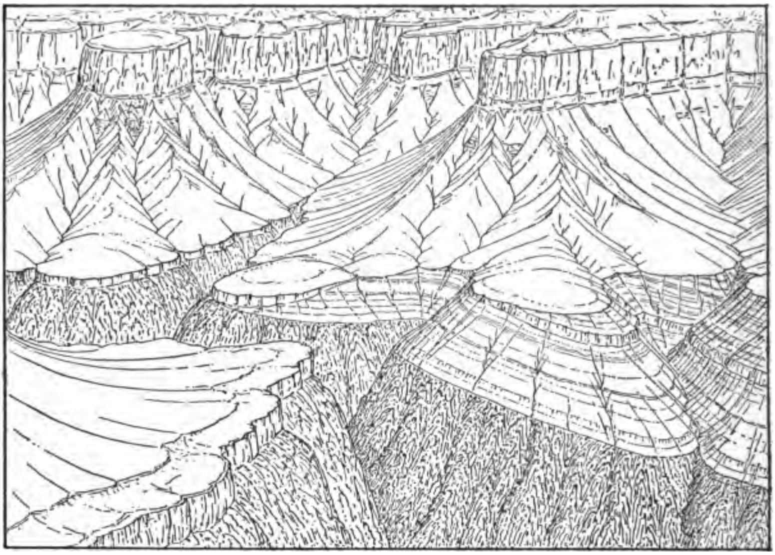


FIGURE 14.

The Algonkian "wedge" between the crystalline foundation and the palæozoic series; looking north across the canyon from near Hance's on the Coconino river. Constructed from rough sketch.

---

[1] The view of this structure given by Powell (*a*, p. 212, Figure 79) is somewhat misleading, for it represents the inclined members of the Grand canyon series with a horizontal base, as if they were examples of cross bedding on a gigantic scale. The correct relation is shown in figures by Walcott (*b*, p. 551; *e*, p. 507 — this from a drawing by Gilbert — and *c*, p. 553) and by Frech (p. 477). It may be noted that a sheet of basalt or diabase, which occurs near the base of the Unkar series and which has been regarded as contemporaneously interbedded by Walcott (*e*, p. 508) and doubtfully described as either an intrusion or a surface flow by Frech (p. 477), seemed to us to be an intrusive sheet or sill, because it appeared to step from one bedding plane to another by distances of a score of feet or more at one or two places; but this opinion is based only on field-glass observation at a distance of over a mile.

tural plain, from which more than six thousand feet of strata have been removed. There have, then, been two periods of essentially completed erosion, marked by the floor of the Grand canyon series and by the floor of the palæozoic series, and one period of far advanced erosion, marked by the skyline of the Kaibab; and three alternate periods of enormous erosion elsewhere to supply the strata locally deposited in the Grand canyon series, the palæozoic series, and the mesozoic series; and the work done in any one of these six periods far outranks that thus far accomplished in the erosion of the canyon. Excepting the periods of mesozoic deposition and erosion, all this history is recorded in the canyon with the clearness that one ordinarily sees only in colored diagrams on a blackboard, and with infinitely greater detail and impressiveness.

The Two Unconformities. — The double unconformity associated with the "wedge" of the Grand canyon series (Figure 14) deserves special attention. The floor on which these strata rest is of remarkable evenness, in spite of the great deformation of the fundamental schists. It is exposed in the section on the northern wall of the canyon for the greater part of a mile, dipping under the river at the lower (eastern) end and terminated at its upper (western) end by the surface of the second unconformity. The line here seen may be taken as a fair sample of a large area of the floor on which the Grand canyon series rests, because it is exposed by the chance section made by the river, whose course was originally selected with no regard whatever for the then deeply buried crystalline foundation of the region. The whole surface must have been much larger than the part seen in the canyon; for if the crystallines were evenly truncated here, they must have been similarly worn down over a large extent of adjoining territory; and, moreover, a formation that measures ten thousand feet in thickness, like the Grand canyon series, cannot be of merely local development. The conclusion seems compulsory that before the deposition of the Unkar strata (the lower members of the Grand canyon series, Walcott, *e*, p. 506) the crystalline rocks were reduced to a plain of admirable evenness, either by marine or by subaerial forces; and however many cycles or partial cycles of erosion were devoted to this ancient task, the last cycle must have been undisturbed until it was very far advanced.

The floor on which the palæozoic strata lie was formed by extensive erosion after the tilting of the crystalline schists with their heavy cover of the Grand canyon series, the compound mass being planed down to an almost even surface. The Kaibab section of this floor is over fifty miles in length along one side of the river, or about forty miles in a direct line. Through very nearly all this distance, the floor is covered by the basal (Tonto) sandstones of the palæozoic series. When the actual contact is seen, it is found to be ragged, but in the twenty-mile stretch that I saw, the vertical inequalities of the floor were trifling in comparison to its horizontal extent. A few miles west of the Grand view trail into the canyon, a broad flat mound of the crystallines rose high enough in the northern wall of the canyon to interrupt the whole thickness of the Tonto sandstones (Figure 15), but this was the only significant unevenness of the surface between the Tonto and the schists visible in that direction. A short distance east of the apex of the "wedge," the more resistant members of the older series are not so well planed down as are the crystallines just west of the same point, and the Tonto sandstone is there greatly reduced in thickness or altogether wanting for large fractions of a mile. But these inequalities in the

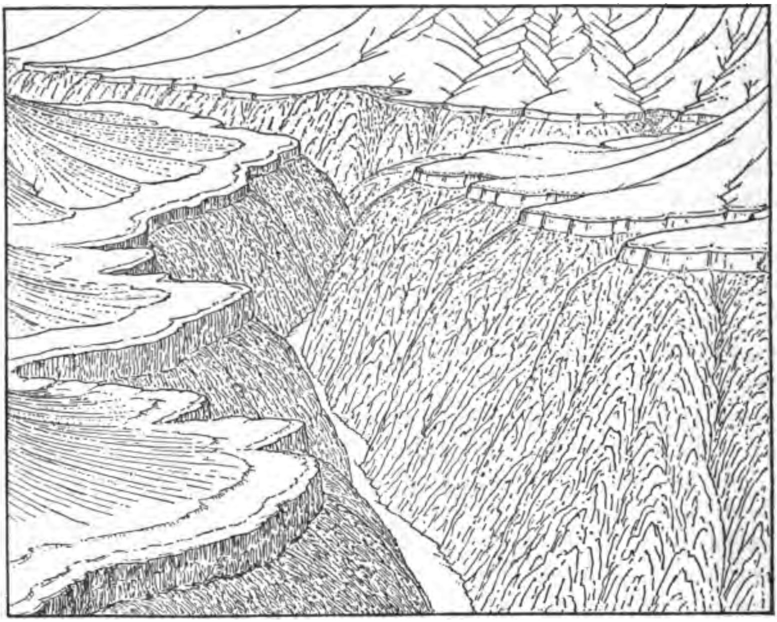


FIGURE 15.

The canyon in the crystallines, looking down the river (northwest) from Coppermine spur, Grand View trail. The crystalline floor is generally covered by the Tonto sandstone; but a low crystalline monadnock rises through the Tonto in the distance. Drawn from a sketch.

palæozoic floor are of small value compared to the strong relief that must have been developed in the mature stage of erosion on the tilted Grand canyon series and their underlying schists. The ancient floor was certainly a topographically old surface, in a far advanced stage of its erosion cycle.

The extension of the palæozoic floor further west may be briefly sketched. Powell noted "patches of granite, like hills thrust up into the limestone" in his passage through the Kanab section of the canyon (*a*, p. 92). Dutton describes the floor in detail, emphasizing its small relief, and Holmes made an admirable drawing of the southern wall in the Kaibab section of the canyon (*c*, pp. 178–181, 207, 209, Plate XXXV.). Newberry wrote, when describing the section in the Shivwits plateau: "The erosion of the cañon has beautifully displayed the ancient surface of the granite, and shows it to have been extremely irregular; hills several hundred feet high, many of which have precipitous sides, and deserve the name of pinnacles, have been exhumed from the sediments in which they were enveloped. The sandstones and shales are seen to have been deposited quietly around them; their strata, nearly horizontal, abutting against their sides" (p. 58). Gilbert says that "all along the southwestern border of the plateau region in Arizona, the Archæan schists and granites are seen beneath nonconforming members of the Grand cañon rock system; usually the Tonto sandstone" (*a*, p. 186), and his diagrams represent the contact of the two systems by a straight line. My lamented classmate, Marvine, records similar observations (p. 199). A photograph of a point in the western part of the Grand canyon, near Peach spring, Ariz. (View No. 173, taken by W. H. Jackson and Co., Denver, Colo.), shows the crystallines as evenly capped by the Tonto as they are in the Kaibab section. The palæozoic floor is thus traced for over a hundred miles from the Kaibab section, and in spite of its inequalities, it is nearly everywhere capped by the lower palæozoic strata. It was certainly a surface of moderate or small relief.

The slope by which the crystallines descend to the river under the stratified rocks has different profiles east and west of the apex of the "wedge." Under the Unkar, the slope is uniformly steep from top to bottom. Under the Tonto, a bench of crystallines stands forth for several hundred feet, and then bends by a strong curve to a slope as steep as that beneath the Unkar (Figures 14 and 15). The persistence of this feature in the view down the river from a point over the edge of the "wedge" is remarkable, and strongly suggests that the crystallines under the Tonto are weaker in their upper than in their lower portion. It occurred to me that this might be the result of deep weathering of a pre-Tonto peneplain, before it was buried by the palæozoic series, and that the incursion of the Tonto sea over the peneplain was too rapid to allow the waves to abrade anything more than the superficial soils; thus leaving the weakened rocks to reveal their weakness in the canyon profile to-day. The sub-Unkar floor, on the other hand, seems to have been smoothly worn down to firm rock by marine abrasion before it was covered by Unkar sediments; but whether the advancing Unkar sea destroyed great mountains of schists or merely planed off the soils and weathered rocks of a pre-Unkar peneplain is an unsolved question.

CORRELATION OF WATER STREAMS AND WASTE STREAMS. — The palæozoic walls of the canyon in the Kaibab exhibit a combination of cliffs, slopes, and platforms in great variety, appropriate to the horizontal structures on which they are eroded. The widening of the canyon here has not yet produced broad benches or platforms, although a systematic beginning of their development is repeatedly observed; but in the Kanab, Uinkaret, and Shivwits sections of the canyon the upper surface of the Red-wall group has been denuded to form a broad platform, called the esplanade by Dutton, to which fuller reference will be made below. Returning to the Kaibab, a pleasing comparison may be made between the path of a running stream of water along the valley bottom and that of a creeping stream of waste down the valley side; the simplest examples for comparison being in horizontal strata such as are so magnificently displayed in the canyon walls. In both cases, graded slopes are first established in discontinuous stretches on the less resistant strata, while cliffs remain ungraded on the outcrops of the stronger strata. The close analogy of the two cases is brought to mind by comparing a plunging fall of water, leaping down the nearly vertical face of a resistant stratum in the valley bottom, with the discontinuous fall of rock waste over the cliffed outcrop of a resistant stratum on the valley side. The evenly graded reach of the water stream on the weaker strata above the fall corresponds with the flat platform in the valley walls above the cliff; and the "cave-of-the-winds" in the weak strata just behind the waterfall corresponds with the hollow or "rock-house" beneath the overhanging base of the cliff; the scanty heap of rock fragments beneath the waterfall corresponds with the sheet of rock waste (with the coarsest fragments lowest down) that cloaks the under slope of weak strata from the rock-house down to the back or inner margin of the next platform below. It is natural that the proportionate development of the several elements, cliff, rock-house, talus-slope, and platform on the valley side, should vary from that of the corresponding elements, cliff, cave-of-the-winds, rock-heap, and reach along the valley bottom, on account of the difference of behavior between a sluggish stream of waste and a nimble stream of water. In the latter, the vertical element of form is reduced to a small fraction of the horizontal at an early stage of the cycle; while in the former, the vertical dimension remains strong until the stage of maturity is past.

Graded reaches make the greatest part of even a young river, but graded platforms widen slowly on valley sides and attain no great breadth until late maturity. It is along these graded reaches that the finer waste from the rock-heap, as well as from further up-stream, is steadily carried forward; comminution of rock waste is active, but erosion of the rock bed is here extremely slow. Rock-heaps under waterfalls are so unimportant topographically that they are seldom included in geographical descriptions; yet they are really characteristic elements of a young river's course in structures of the kind here considered. Talus slopes on valley sides are of much greater dimensions; so great indeed that they form a systematically graded surface. Their grade is steep compared to that of the platform because their waste is coarse. These accumulations of coarse waste, both rock-heap and talus, consist chiefly of fragments broken from the cliff above; the fine waste that is weathered from them is carried forward or down-stream, while the surface on which they rest retreats backward or up-stream. Rock-heap and cave-of-the-winds vary inversely; the sum of their vertical measure together with that of the face of their fall ledge (a constant) makes the height of the fall: talus-slope and rock-house are similarly related. The cave-of-the-winds is larger but less habitable than the rock-house; but in the wet as well as in the dry cave, air-movement is an important factor of erosion. The cliffs in the two cases are so much alike that they need no further comment.

The strongest fall-and-cliff-makers endure longest, while the less strong ones are sooner worn back until they disappear under a graded reach or platform (Gilbert, *b*, p. 100), or retreat into the cave-of-the-winds or the talus-slope under a master cliff. Among the disappearing falls and cliffs, those which are down-stream from a very resistant ledge will be the first to vanish, because their more rapid recession will soon push them back under the slowly retreating master ledge; the canyon walls give many examples of this kind. On the other hand, the disappearing falls and cliffs will remain in evidence for a much longer time if they are up-stream from the master ledge, for there they must recede until they are concealed beneath the backward extension of the gently sloping graded reach or platform below them. Thus a master ledge promotes the development of a high fall or long talus-slope beneath it, and of a long reach or broad platform above it; and when this relation is established, the number of separate elements of form in valley bottom or on valley side is much less than it was in earlier youth. The great escarpments of the High plateaus exhibit the concentration of all the large and small cliffs of youth in a relatively small number of great cliffs in late maturity; and thus still again confirm Dutton's opinion that the erosion of the plateaus and the erosion of the canyon took place in different cycles, separated by a strong uplift of the region.

The general principles here reviewed are of wide application, but in regions of moderate relief and moist climate, the forms of valley sides are seldom analyzed: certainly they are frequently overlooked in geographical descriptions. In the Grand canyon district, where the relief is on a huge scale, and where the arid climate lays bare every topographical detail, the elements of form assumed under moving streams of waste on valley sides are conspicuous; they are glorified by mere magnitude so that one is tempted to treat them as a new class of topographic forms, until it is recognized that they are only new variations on an old class, examples of which are to be found in all regions of horizontal structure. The canyon walls in the Kaibab and the great mesozoic "terraces" that overlook the plateau from the north exhibit the earlier and later stages of all these forms with great clearness.

Cirques, Cusps, and Niches. — The many variations in the horizontal pattern of the cliffs in the canyon walls have been briefly described by Dutton (*c*, pp. 258, 259). The cliff outline, as seen in plan, has two expressions (Figure 16). In some cases, the re-entrants of a cliff are sweeping concave curves, but little notched, while the intervening salients are sharply attenuated cusps. In other cases, the re-entrants are narrow and acute notches, while the salients are broad and rounded spurs. The difference between these two cases seemed to depend partly on the drainage area of the uplands, whose waters are shed over the cliffs from higher levels, and partly on the amount of erosion that the cliffs have suffered; these two factors being indirectly connected.

Where an upland sheds a stream over a cliff, the cliff will be cut back much faster by the stream than it will be weathered back on the inter-stream front; here the re-entrant must be an acute notch; while the adjoining salients will be spurs with rounded front. But where the upland is of so small an area that it cannot gather streams, then the head of the axial line of a re-entrant has no more importance as a stream way than the lines that join it from either side; as a result the retreat of the walls will be of about uniform value for a considerable length of front, and the head of the re-entrant will here assume a concave or cirque-like pattern. At the same time, the widening of the re-entrant will narrow the adjacent spurs to mere skeletons of their original size and sharpen their salients into cusps.

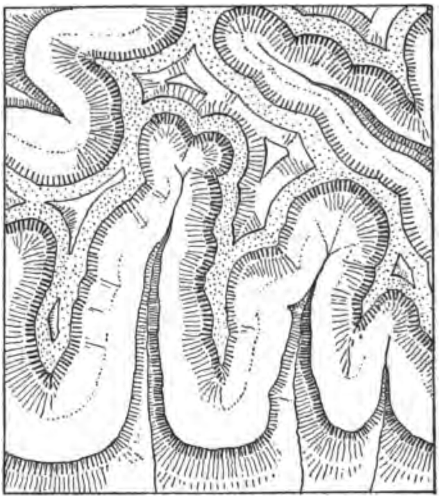


FIGURE 16.

Notches and cusps in cliff patterns. Diagram of two cliff-makers; the lower one showing acute notches between rounded spurs; the upper showing rounded cirques between acute cusps. Slightly modified from Bodfish's map of part of the canyon wall in the Kaibab. (Dutton, c, Plate XLII.)

If this analysis be correct, rounded spurs and sharp re-entrant notches should prevail in the cliffs near the base of the canyon walls, because streams will generally descend into such re-entrants from the higher slopes; unless, indeed, time enough has elapsed for the strata overlying a low-level cliff to have been swept away, and the area of its platform reduced by the widening of adjoining side-canyons, so as to imitate conditions that would prevail only at higher levels in an early stage of erosion. On the other hand, cirque-like re-entrants should prevail in the high-level cliffs that rim the sides of the great spurs of the canyon walls, and the spurs between these cirques should be acutely sharpened cusps. Cirque-like curves should occur in the rim of the plateau only where no significant area sheds drainage from it, and notched re-entrants should occur in the high-level cliffs chiefly at the head of side canyons where back-country drainage is delivered to them. As a consequence of all this, a rather systematic relation should frequently be found between the two sets of forms; the curved re-entrants of the higher cliffs should frequently stand back of and above the sharp re-entrant notches of the lower cliffs; while the sharp spurs of the upper cliffs should project forward along the axis of the rounded spurs of the lower cliffs.

As far as this scheme was tested on the ground, it seemed to give reasonable explanation to a good number of examples; but unfortunately it was not reduced to formal statement until after leaving the canyon; hence, as so often happens, the observations made on the ground were less critical than they might have been if they had been immediately accompanied by analysis.

The niches of the massive Red-wall limestone, described but left unexplained by Dutton (*c*, p. 260, Plate XLI.) seem to exemplify a special case of a problem that McGee has discussed in connection with the "origin and hade of normal faults" (*a*, p. 296). The niches all occur over the heads of subordinate ravines or gulches, and are, therefore, to be associated with the sapping by the underlying weaker strata and the falling away of the basal part of the massive limestone. In the absence of numerous planes of bedding and jointing, the upward breaking of the rock may be compared to the upward propagation of a fault; and McGee shows that in such case the fracture must be a curved surface with decreasing hade upwards, so that the broken face may eventually become vertical or even overhanging. The overhanging arch by which the niche is covered seems to correspond to the upper part of such a fracture.

THE ESPLANADE. — Although the Kaibab and the Uinkaret are only forty miles apart, the canyon in these two plateaus exhibits very unlike cross-profiles. In both, the double cliffs of the upper Aubrey are repeated with similar outlines. In the Kaibab, a platform of moderate width is worn on both the Red-wall group and the Tonto sandstone, the lower one being rather wider than the upper, and the two being separated by the huge Red-wall cliff and the long gray waste-covered slope of Tonto shales beneath it. In the Kanab and Uinkaret sections, as seen from Vulcan's throne at the mouth of the Toroweap valley, the Red-wall platform is greatly widened; it becomes a broad floor, stretching far up and down the canyon, and fully deserving the name, esplanade, given by Dutton; but the Tonto platform is wanting; the cliffs from the top of the Red-wall descend with their steepness little diminished nearly to the river, enclosing the narrow inner canyon or chasm; while the Aubrey walls of the upper or outer canyon are five miles or more apart. It is significant that the floor of the esplanade everywhere lies on the same stratum, namely, a calcareous sandstone; the upper member of the Red-wall group.[1]

Two Theories of the Esplanade. — Dutton explained the esplanade as a mature valley, eroded during a pause in the uplift by which the broadly denuded plateaus gained their present altitude. During this pause, "the river sought and quickly found a new base-level at the bottom of the great esplanade of the Grand cañon. . . . The cliffs . . . receded away from the river, gradually developing the broad avenue of the outer chasm. . . . Again the country was hoisted, this time more than before. . . . Swiftly the inner gorge was scoured out, and the chasm assumed its present condition. At present the uplifting force is inactive . . . and the river has nearly but not quite reached another base-level" (*c*, p. 121).

It had been suggested to me before our trip to the canyon that it was not necessary to assume a pause of this kind in the later uplift of the plateaus in order to account for the esplanade, for its relation to the resistant Red-wall group was such as to indicate its dependence on structure rather than on a former baselevel. Several reasons for adopting this view presented themselves.

Comparison of the Kaibab and the Kanab Sections. — In the first place, if the form of the canyon in the Uinkaret, Kanab, and Kaibab plateaus were dependent on recent sub-cycles or episodes of erosion, rather than on structure, some indication of the esplanade ought still to be apparent in the Kaibab section at an altitude corresponding with that so well maintained further west; but inasmuch as the uplifts of the Kaibab are believed to be of much earlier date than the erosion of the canyon, the esplanade ought to stand at a lower geological horizon in the Kaibab than in the Kanab. No trace of an esplanade is, however, to be recognized in the Kaibab; the descent from plateau to river is there accomplished by a general incline, broken only by the benches of the Red-wall and Tonto groups, as stated above. On the other hand, the slopes of the Kaibab walls and the cliffs and esplanade of the Kanab walls are easily explained if they are dependent on local structural conditions; and there is independent evidence that the appropriate conditions actually occur. It is evident that if the Tonto shales that form the slope between the Red-wall and the Tonto cliffs in the Kaibab should become more resistant as they pass westward into the Kanab, their face would steepen, and the Red-wall cliff would come to stand more immediately over the Tonto; at the same time the Red-wall platform would broaden to form the esplanade. Observations are not lacking to support this supposition. Gilbert noted that, at the entrance of Kanab creek into the main river, the Tonto shales are of "firm texture" (*a*, p. 70). Dutton says more explicitly: "In the Kanab division the whole series of nearly 2,500 feet thickness [Red-wall and below] is wonderfully massive, and the partings of the strata are comparatively few. In the Kaibab the great 750-foot limestone is as solid as ever, but most of the other members have become laminated much more minutely than in the Kanab and Uinkaret, and are of more perishable texture" (*c*, p. 257). As these values of resistance are precisely such as would undermine the Red-wall cliff-makers in the Kaibab and support them further west, a structural explanation for the esplanade seems to be sufficient.

---

[1] In Gilbert's section of the canyon at the mouth of Kanab creek, a heavy cross-bedded sandstone of the lower Aubrey is placed at the floor of the esplanade, and no such sandstone is shown in the wall of the outer canyon above the esplanade (*a*, p. 70, Figure 38); while the section of the Shivwits canyon sets the floor of the esplanade on the Red-wall group, and places the cross-bedded sandstone of the Aubrey as a cliff in the wall of the outer canyon. Gilbert explains this variation by the statement that the order of the hard and soft beds in the lower Aubrey is not constant (*a*, p. 177); but Dutton says: "The cliff formed out of the upper and lower Aubrey series is very remarkable for the constancy of its profile throughout the entire extent of the great chasm." As far as my own observations went, they agreed with the latter view. It is possible that the cross-bedded sandstone which Gilbert placed on the floor of the esplanade at the entrance of the canyon of Kanab creek into the Grand canyon was really the calcareous sandstones which as a rule forms the upper member of the Red-wall group, capping its great cliff.

Eastward Fading of the Esplanade. — In the second place, if the eastward extension of the esplanade be traced on the topographical maps, it gradually loses definition by decrease in its breadth and by increase in the number of ravines that break its front; and in the easternmost part of the Kanab it can hardly be recognized. This is best seen by tracing the southern side of the canyon, for on approaching the Kaibab, the form of the northern canyon wall is much complicated by the displacements that occur there, and bedded structure has not alone a full control. A gradual change of form of this sort is an appropriate consequence of the structural origin suggested for the esplanade.

Relation of the Inner and Outer Canyons. — In the third place, the position of the inner canyon along the middle of the esplanade is, as was suggested to me several years ago by Mr. C. H. White (then one of my graduate students, now instructor in mining at Harvard), singularly significant of a single period of erosion. This may be understood by considering the two alternatives in order. If the esplanade represented a mature valley floor, broadened by the lateral swinging of the river during a lower stand of the land, rather than by the rapid wasting of the weak lower Aubrey layers in contrast to the persistence of the strong Red-wall group, then when renewed uplift revived the process of canyon cutting, the river must have occupied an irregular path along the esplanade, and the inner canyon would have been cut at one place near the northern wall of the outer canyon, and at another near the southern wall. This condition is actually illustrated in the valley of the Rhine; here a narrow inner gorge is incised in the flat floor (esplanade) of a broad trough which in turn is eroded beneath the bordering uplands; a structural origin for the trough is inadmissible because the rocks are greatly deformed; and, moreover, river gravel and silt still cover the floor of the trough. The narrow gorge is intrenched irregularly along the trough floor, sometimes turning so far to one side that a continuous descent leads from the high upland directly to the river, while a correspondingly broad mid-level floor remains on the other side. The same relation occurs in the valley of the Moselle, whose young gorge meanders conspicuously from side to side in the floor of the mature trough. The valleys of the Lot and the Dordogne in southwestern France exhibit similar features, except that the younger or inner member of the composite valleys are here opened wide enough to have scrolls of incipient flood plain on one or the other side of the river, while flood plains are as yet only just begun in the gorges of the Rhine and the Moselle.

If, on the other hand, both the outer and the inner canyons of the Colorado are the work of a single cycle of erosion, and the esplanade is of structural origin, then it is necessary that the walls of the outer canyon should retreat symmetrically on either side of the inner canyon, and that the inner canyon should bisect the floor of the esplanade thus produced. This case would correspond to that of all one-cycle valleys in horizontal strata, where the symmetry of the benches and slopes on the two walls results from their essentially equal retreat under the weather. Innumerable illustrations of such symmetry may be seen in the side canyons of the Kaibab section, where the Red-wall cliffs are placed symmetrically with respect to the narrow gorges in the Tonto sandstones below and between them; the detailed map of part of the canyon in the Kaibab by Bodfish already referred to (Dutton, *c*, Plate XLII.), gives good illustration of many examples of this kind.

Now returning to the facts, there seems to be little doubt that the inner canyon bisects the esplanade. Its medial position is very striking in the majestic view that we had of both these features eastward from Vulcan's throne; a view made famous by Holmes's wonderfully effective drawing (Dutton, *c*, Atlas, sheet VI.). All the published maps and sections of the district exhibit this arrangement in the most systematic manner through the Kanab and Uinkaret plateaus, and as well in the lateral canyons of Cataract and Kanab creeks as in the main canyon. Even the first accounts of the canyon made mention of the medial course of the inner chasm. Ives, descending from the plateau south of the Kanab section by a branch canyon, reached a floor (a branch of the esplanade) which, when seen from the enclosing cliffs, looked smooth, but which was really covered with hills thirty or forty feet high; "along the centre we were surprised to find an inner cañon, a kind of under cellar" (p. 107). Powell's first mention of the esplanade, as seen from the cliffs near the border of the Kaibab and Kanab plateaus, is as follows: "The walls seem to rise very abruptly, for two thousand five hundred or three thousand feet, and then there is a gently sloping terrace, on each side, for two or three miles, and again we find cliffs, one thousand five hundred or two thousand feet high. From the brink of these the plateau stretches back to the north and south, for a long distance. . . . The effect of the terrace is to give the appearance of a narrow winding valley, with high walls on either side, and a deep, dark, meandering gorge down its middle" (*a*, p. 92; also p. 196). It should be noted, however, that the topographical maps show the Shivwits section of the canyon to have walls of less symmetrical form than prevails further east; but not having seen this part of the canyon, I shall not venture to discuss its complications.

Relation of the Esplanade to the Toroweap Fault. — Finally, it may be noted that the early date given on page 146 for the Toroweap-Sevier fault is not at all inconsistent with the discontinuity of the structural esplanade where it crosses this fault-line; for if the floor of the esplanade is of structural control, it would be opened at whatever level the upper surface of the Red-wall group occupied at the time of the erosion of the canyon. If, on the other hand, the esplanade had been controlled by a former baselevel, its discontinuity at the Toroweap would demand a very late date for the fault, as Dutton concluded when he wrote: "It seems very plain that the outer chasm had been formed and attained very nearly its present condition before the [Toroweap] fault started" (c, p. 94). So recent a date of faulting seems inconsistent with the evidence presented in the section on the Pipe spring fault.

Conclusion as to the Origin of the Esplanade. — In view of these various considerations, it seems necessary to conclude that while many partial cycles of erosion may have preceded the long pause during which the broad denudation of the plateaus was completed, only a single uplift and a single down-cutting are recorded in the canyon. It should be noted that Dutton considered this supposition, but rejected it. Speaking of the esplanade, he said: "We might explain it by assuming the rocks of the inner gorge to be much more obdurate than those above. This is true in part, but still the difference in this respect is insufficient. A much more satisfactory explanation is found in the supposition that the broad esplanade of the cañon between the upper palisades was an ancient base-level of erosion" (*b*, p. 121). In another place he explains the difference between the Kaibab and Kanab sections of the canyon in the following manner: "The causes which have produced in the Kaibab a topography differing so widely from that which is seen in the other divisions of the chasm may be readily explained. The Kaibab is now, and throughout the period of evolution of the chasm it always has been, higher than the other plateaus. Corrasion has, therefore, penetrated there more deeply than elsewhere. It has, moreover, laid bare the edges of the softer beds underlying the Red Wall, and the rapid decay of these lower beds has undermined and wasted the Red Wall to a great extent. In the other divisions of the chasm corrasion has only at a very recent period cut below this great series of hard limestones. . . . Besides the greater altitude leading to deeper corrasion, the climate of the Kaibab is moister, and the degrading forces are, therefore, more efficient" (*c*, pp. 257, 258). From the other point of view, it seems as if these several considerations might legitimately be adduced to account for the esplanade as of structural origin; for if differences of structure, altitude, and climate all lead to differences of form between the Kaibab and Kanab sections, there seems to be all the less need for explaining the esplanade in the Kanab plateau by a pause during the uplift. On the other hand, the earlier date of the Kaibab arch must have led to the erosion of the Aubrey limestones on its crest much earlier than the same strata were attacked in the erosion of the canyon further west. The Kaibab must have been trenched, as has been already suggested, to a depth of one thousand or one thousand five hundred feet (probably revealing the lower Aubrey group, but not cutting through it) before the introduction of the canyon cycle, and a broad floor, an esplanade, must have been opened through it, indifferent to structure, at the level of the denuded plateaus on the east and west. Since then there has been time for the deep cutting and rapid widening of the new canyon to destroy all traces of this floor and bring about the correlation of form and structure that to-day so fully characterizes this section of the canyon.

HINTS FOR A VISIT TO THE CANYON. — A few words as to the descent into the canyon from the Coconino rim opposite the Kaibab, with special reference to a sight of the "wedge," may not be out of place. The best geological map of this district is that made by Walcott (*e*, Plate LX.). The Grand View trail, descending from Cameron and Berry's, gives a convenient approach to the apex of the "wedge." Horses for riding and donkeys for carrying a small pack of blankets and provisions can be hired at the hotel; but if the visitor goes on foot, an early morning start should be made, before sunrise, if possible, as the temperature in the canyon is very high over the noon hours during clear summer weather. It would be certainly a great advantage to plan a visit at the time of full moon, so as to be able to use the night hours for at least part of the climb out of the canyon. The Coppermine spur may be easily reached in the morning before the greatest heat sets in, and noon may be passed at its end on the Red-wall platform, studying the "wedge," as exposed in the northern wall, and examining the canyon to the east and west. A light shelter of canvas to keep the sun off would be a great comfort in this work, as shade is scanty and the glare from the bare rocks is fatiguing while one is attentively studying details of structure and form. A field-glass greatly aids and extends observation in all parts of the canyon, for distances are large. A camp for the night may be made in the side canyon next west of the Coppermine spur, where a small stream is found just above the level of the basal Tonto sandstone; but the descent to this spot will be more enjoyed if it is left till late in the day, as the trail down a gulch in the Red-wall cliff is directly exposed to the afternoon sun. A second day can be well spent in descending to the river and in examining the palæozoic floor; or in passing around the Tonto platform at the base of the Coppermine spur so as to enter the next ravine on the east, where the "wedge" seemed to be exposed on the south side of the canyon. When viewed from above, the various slopes and platforms seem very smooth, as if one could walk over them without difficulty; but when actually upon them, the smoothness vanishes; the dimensions of every item of form are magnified far beyond expectation; everything is rough and rugged, and walking is tiresome work. A third day can be given to various problems regarding stratified structures which are here open to observation in a larger way than almost anywhere else in the world. The mere sight-seer may be content with a brief trip down and back, but the geologist who can go as far as the canyon ought to spend several entire days in its depths. We were unfortunately so hurried as to have only an afternoon, a night, and a morning for the canyon.

If the canyon is visited from the north, the trip may be made on horseback or with wagon from Belknap station, Rio Grande Western railroad, southward to Kanab, and thence either southeast to the Kaibab or southwest to the Uinkaret plateau and the Toroweap valley. The former trip repeats the views seen from the Coconino rim, but it is without the advantage of good trails by which the descent may be made to the river. The latter takes the observer to a great field of volcanic phenomena as well as to the brink of the canyon at a most interesting point. After recent rains, water-pockets can be depended on for camping near Vulcan's throne; but if the season has been dry, water must be brought from Oak spring on the Uinkaret. Although this is troublesome, it is entirely feasible. Two nights and a day are the shortest time that should be wisely allowed to this wonderful spot: it was a real hardship that our party had only a day for the ride from Oak spring to Vulcan's throne and back.

Former Climates of the Grand Canyon District.

DIVERSE OPINIONS OF EARLY OBSERVERS. — The several opinions expressed by Newberry, Powell, and Dutton as to the former climates of the region under discussion seem to me difficult to maintain, so many are the doubtful elements in problems of this class. Newberry inferred a former greater rainfall (p. 47), apparently because of the immense amount of denudation that has been accomplished; but until more is known as to the time occupied in the great denudation, it is impossible to make inferences as to its rate, and hence as to the strength of the eroding and transporting agencies, and the rainfall that excites them. Powell inferred a long-maintained arid climate, because "in a region of country where there is a greater amount of rainfall, the tendency is to produce hills and mountains, rather than plateaus and ridges, with escarpments" (*a*, p. 204). It may be urged against this view that escarpments of a strength appropriate to their capping layers occur in better-watered regions, as in the Catskill mountain front of eastern New York, and in the Swabian Alp of southern Germany; and that the cause of the great cliffs of the Grand canyon district is to be found chiefly in the massive thickness of the resistant strata that guide them, and in the weakness of the underlying strata that sap them. Truly, the sharpness of the cliffs is highly suggestive of aridity, but a relatively short arid period would suffice to sharpen the cliff profiles, even if they had been somewhat dulled by a previous humid period.

The narrowness of the canyons, so generally explained by the aridity of the plateaus through which the vigorous Colorado flows, certainly finds a large part of its explanation also in the recency of the uplift by which the canyon cutting was initiated, and in the massiveness of the resistant layers by which the canyon walls are defended. The side canyons by which the plateaus are dissected are not insufficient in number even for a moist climate; they are much more numerous than the perennial side streams. The latter are notoriously rare: the former are present in good number, and in wet weather they are actively washed by their temporary floods. It is true that the side canyons are of so steep a descent along their floors that they lose much of their depth at a moderate distance back from the main river; but this may be a consequence of recent uplift as well as of slow corrasion. The side canyons branch frequently enough to satisfy an active drainage system, and certainly there is no deficiency of ramifying valleys on the higher uplands where the surface is so thoroughly and maturely dissected. It is the steep grade of the waste on the floors of these valleys that suggests a development under an arid climate, and such a grade would be soon acquired under a dry climate even if the valleys had once been cut somewhat deeper under a moist climate. Hence, even in the more recent past of the canyon cycle, a humid climate seems no more impossible than unnecessary, and in the more distant past of the plateau cycle, climates of any and all kinds might have prevailed, as far as the present topography of the Grand canyon district is concerned.

Moist Miocene and Arid Pliocene Climates. — In contrast to Powell, Dutton concluded that the Miocene (plateau cycle) was humid. This opinion seems to have been based partly on the occurrence further north of extensive fresh-water deposits of Miocene age, usually interpreted as having been laid down in large lakes, whose existence pointed to a good supply of rainfall (*c*, p. 223), and also on the apparent desiccation near the beginning of the Pliocene (canyon cycle) of certain branches of the Colorado, whose previous existence implied the continuance of a good water supply, just as their later disappearance implied its cessation (*c*, pp. 99, 201, 223); the arid climate thus introduced continued to the present day, except for the occurrence of an inferred pluvial period corresponding to the glacial period elsewhere.

Other interpretations seem to me possible for several of the facts here brought forward. I have elsewhere presented some considerations regarding the possible explanation of at least some of the fresh-water Tertiary deposits of the Rocky mountain region as fluviatile rather than as lacustrine formations (*b*, p. 360), and in so far as this alternative explanation is found applicable, the evidence above quoted for the humidity of the plateau period will weaken. The argument for a change from humid to arid climate, based on the apparent disappearance of certain streams, seems to me open to serious question; it is considered in the next section. The ravines that are adduced by Dutton as the evidence of a brief Pleistocene pluvial period appear to be open to explanation under as arid a climate as prevails to-day, as will be specially considered in the next section but one. Thus the climatic history of the district becomes extremely uncertain. Whatever conclusions are reached as to the climatic conditions of any period of past time — the glacial period, for example — in surrounding regions may be permitted for the Grand canyon district, but no special climatic conditions are demanded by local evidence. Yet among the several opinions quoted above, the long-enduring arid climate suggested by Powell seems to me the most probable, because for a long time the Grand canyon district has lain to leeward of a mountainous area, and during much of this time the district stood lower than it does now, while the mountains to windward were higher.

THE TOROWEAP. — The Toroweap (T, Figure 1) has already been referred to as a valley that has been eroded along or near the southern part of a long fault-line that comes from the northeast past Pipe spring; it is part of the boundary between the Uinkaret and Kanab plateaus. The peculiar feature of the valley now in evidence is its shallowness; for its broad floor leads forward to the level of the esplanade and shows in its surface form hardly any sign of incision to a deeper level. Dutton infers from this that the stream by which the valley was originally eroded became extinct about the time of the latest upheaval of the region, after which the inner canyon was cut down beneath the esplanade by the main river, whose water supply in distant mountains had not been cut off (*c*, p. 99). There are two arguments against this view. First, a number of side canyons in the neighborhood of the Toroweap, of similar or smaller drainage area and equally dry, are cut down to essentially accordant junction with the bottom of the main canyon. A small valley of this kind is seen to enter the main canyon from the south at a short distance west of the South Toroweap;[1] a view of its upper part is included in a drawing made by Holmes to illustrate the dikes in the canyon wall (Dutton, *c*, Plate XVIII.). Although the drainage area from which the wet-weather stream is here gathered is but a small fraction of that which supplies the floods of the Toroweap, this short side valley is cut deep below the esplanade level for several miles back from the inner canyon wall, and as its stream line descends with the steep grade appropriate to short lateral canyons, it makes an essentially accordant junction with the Colorado. A view of the inner canyon from near Vulcan's throne (Dutton, *c*, Plate XVII.) has already been referred to as showing the accordant entrance of two side canyons into the main canyon in the neighborhood of the Toroweap. The same relation obtains in the case of an unnamed side canyon, coming from the north twelve miles east of the Toroweap: its drainage area is similar to that of its high-floored neighbor, yet it is cut down so that its temporary floods may join the main river in perfectly accordant fashion, as far as one may judge from the topographic map of the locality. Many other examples of this kind might be given, as could be inferred from what has already been said in a previous section as to the generally accordant junction of side and main canyons. It, therefore, does not seem possible to ascribe the failure of erosion in the Toroweap to the desiccation of a once permanent stream; for in that case all the neighboring streams in small side canyons must also have been desiccated, and should have high floors; yet as a matter of fact their streams have not ceased to erode effectively.

Secondly, some local obstacle to erosion in the Toroweap would suffice to explain its peculiar form, and such an obstacle certainly occurs there, for the broad floor of the valley has been heavily and repeatedly sheeted over with floods of resistant lava, supplied by the magnificent lava cascades from the Uinkaret, as pictured in one of Holmes's most effective drawings (Dutton, *c*, Atlas, sheet V.). The occurrence of the lava flooring is fully recognized by Dutton, who wrote: "There is reason to believe that at some prior epoch it [the Toroweap] was cut a few hundred feet deeper than its present floor, and was subsequently built up by many floods of basalt coming from the cones on the Uinkaret and by considerable quantities of alluvium washed from its cliffs and overlooking mesas" (*c*, p. 92). We may therefore conclude that in the early stages of the canyon cycle, when the intermittent side streams had cut down their canyons into the Red-wall group and the canyons had already widened somewhat through the sapping of the upper Aubrey cliff-makers by the weak red beds of the lower Aubrey, the Toroweap was flooded with lava, while most of its neighbors remained free from volcanic interference. The streams in the latter continued to deepen their courses, while deepening was practically stopped in the Toroweap. But just as the main canyon has widened above the resistant floor of the esplanade, so the Toroweap continued to widen, hence it is to-day normally broad but abnormally shallow. It is a "hanging valley" because of local volcanic interruption of the normal work of canyon-cutting.

---

[1] I have used this name for a valley corresponding to the Toroweap and apparently structurally continuous with it but south of the canyon.

Directly opposite the Toroweap is a similar high-floored valley (*c*, p. 99), splendidly exhibited from Vulcan's throne, and already referred to as the South Toroweap. Like its northern fellow, it is floored with lava near the main canyon, on which it opens close to the esplanade level (Dutton, *c*, Plate XVIII.). Hence its deficiency of depth again seems to be best accounted for by the difficulty of wearing away its lava sill, an accidental and purely local detail, rather than by a failure of rainfall, which must have been general.

Dutton mentions several other high-floored valleys, which he classes with the Toroweap as indicating a decrease of rainfall at the beginning of or early in the Pliocene (canyon cycle). One of these is the Queantoweap, which follows the Hurricane fault along the boundary between the Uinkaret and Shivwits plateaus (*c*, pp. 99, 115). Not having seen this valley, I shall not venture to express an opinion about its origin, yet it may be noted that a small flow of lava near its mouth is marked on the geological map (Dutton, *c*, Atlas, sheet VIII.); and judging by the great lava cascades that plunge into the valley (*ibid., c*, p. 116), some lava may lie concealed beneath the alluvium of the valley floor. A third high-floored dry valley mentioned by Dutton is that on the summit of the Kaibab uplift (*c*, pp. 194, 197, 223) already discussed and explained as a series of independent anticlinal valleys, and thus seeming to be within reach of explanation without recourse to climatic change. A fourth example is House-rock valley (*c*, p. 201), which has already been referred to as a normal subsequent valley worn on weak monoclinal strata. Taken altogether, the lava-floored valleys, the anticlinal valleys, and the monoclinal valley seem to be indifferent witnesses as to changes of climate in the past.

THE PLUVIAL EQUIVALENT OF THE GLACIAL PERIOD. — There is much probability that the rainfall over the Grand canyon district was increased at those times when ice sheets and glaciers were formed over other parts of the continent; yet it seems to me difficult to find independent proof by purely local evidence that such has been the case. Dutton, however, suggests that evidence of this kind is to be found in the ravines of the Kaibab plateau, concerning which he finds "no conjecture so satisfactory as that which supposes that during the glacial period the rainfall was sufficient to sustain living streams in these ravines and that they were then carved by running water" (*c*, p. 196). The same conjecture is thought to hold true for the ravines of the Paria plateau (*c*, pp. 202, 228). Nevertheless, it is difficult to find valid reason for ascribing the erosion of these ravines only to the glacial period, for it seems admissible to conclude that they can have been in large part eroded by the intermittent streams of a climate as arid as that of to-day. The maturity of many of these ravines in resistant strata indicates that, besides glacial time, some of preglacial and all of interglacial and of postglacial times must have been needed for their erosion; hence instead of ascribing them to the glacial period alone, their beginning may be carried back even into the later part of the cycle of the great denudation, as has already been suggested on page 141. Moreover, existing processes do not seem to be inoperative. The stream beds in the lower ravines of the Kaibab bear every mark of being strongly flushed by occasional wet-weather floods. Well-defined fans of coarse and fine waste extend forward from the mouth of the ravines at the eastern base of the Kaibab into House-rock valley, as has been already stated; and a torrent fan was seen at the western base where the road from Jacob's lake descends toward Fredonia. However slow the erosion of the ravines may now be, it is still going on; indeed, the scantiness of vegetation makes the removal of waste so easy that it may be questioned whether rain and stream work is not advancing here at a comparatively rapid rate, — a rate that very likely far exceeds that which prevails in the peat-covered uplands of much moister regions.

Volcanic Phenomena.

Our interest was frequently attracted by magnificent displays of volcanic phenomena in various parts of the Grand canyon district, but we had no time to turn from our route to study them. A few notes on the more striking things are here presented in the hope that they may prove of service to more leisurely travellers.

The dissection of Mt. San Francisco, as seen from the wagon road that runs northward from Flagstaff along the western base of the mountain, suggested a simple terminology for spurs and ravines that might perhaps be serviceable in detailed descriptions of mountain forms. The scheme is illustrated in the accompanying figure, 17, which repeats some of the features illustrated in the diagram of the Permian scarps (Figure 9). I shall hope to return to this phase of morphology at some future time. The young ash cones, still holding unbreached craters, were numerous in the volcanic field north of Mt. San Francisco (Figure 18). About ten miles west of Hull spring (on the Flagstaff-canyon road) a large ash cone was seen with a great breach in its eastern

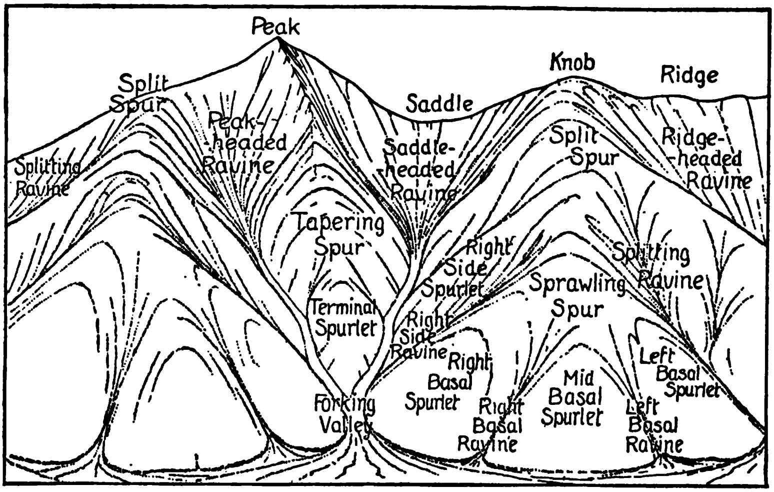


FIGURE 17.

Diagram to illustrate a proposed terminology of spurs and ravines. Constructed from several sketches of the western side of Mt. San Francisco, a dissected volcano.

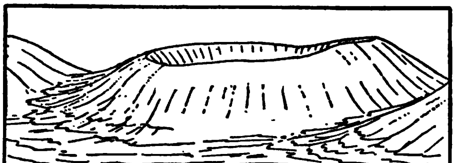


FIGURE 18.

An ash cone and crater, north of Mt. San Francisco and east of Hull spring.

slope, a promising specimen for the study of the structure of such cones. One of the northernmost of the eruptions in this field (Y, Figure 1) seems to be also one of the youngest; it lay several miles south of the rough trail that we followed eastward from Hull spring to the Flagstaff-Tuba road, and as seen at that distance it seemed to form a ragged black mesa, two or three hundred feet high. The various relations of lava flows to small valleys were beautifully exhibited in the same district. In one case a flow banked against the scalloped escarpment of the upper Aubrey, and a little waterway has since been eroded along the line of junction, with yellow-gray limestone on one side and black lavas on the other; this was well seen on the canyon road, a few miles north of Hull spring. Further east, we followed valleys eroded to a depth of two or three hundred feet in the Aubrey layers, and then floored with streams of lava from some neighboring cone. In one narrow valley of this kind, the wash of waste from the walls seems to have prevented the formation of new waterways along the lava margin; here the present stream bed lies for a distance on one side of the valley, then trenches obliquely across the lava and follows its other side for a stretch. In a broader valley, the lava surface was untrenched, and new waterways ran persistently along its margins, this being evidently the incipient stage in the formation of a lava mesa. At Lockett's tank (probably several miles north of Black tank of the topographic map) a narrow canyon of moderate depth in the Aubrey limestone has been filled nearly to its brim with a slender but heavy lava flood, but at present the stream has re-excavated part of its valley, consuming the terminal part of the lava flow for half a mile or more, although leaving scraps of lava here and there, frozen to the walls; and at the head of the new valley is an abrupt fall from the surface of the lava that still remains (Figure 13). Here the wet-weather floods have scoured a basin, in which water remains long after the supplying storm has cleared away; cattle tracks converge on the dry upland from all sides towards this tank.

A narrow dike was noted on the west-facing slope of the Triassic escarpment, just south of the valley of the Moencopie and not far from Tuba; the dike formed a sharp ridge, quite unlike the more tabular forms normally associated with the escarpment.

The great lava cascades that descend from the Uinkaret into the Toroweap and even into the canyon itself are among the most magnificent geological phenomena of the region. Our camp by Oak spring, south of Mt. Trumbull, was at the scarped edge of one of the younger lava flows of the Uinkaret; and the youngest flow of that volcanic field lay a mile to the east (Powell, *a*, p. 131; Dutton, *c*, p. 111, Atlas, sheet IX., lower view); we crossed it on the way down into the Toroweap, and came back by a trail that ascended one of the great lava cascades. A young ash cone stands on the tabular top of Mt. Trumbull, whose mass is but the remnant of a once much larger lava mesa; the young cone was peculiarly placed near its southeastern end of the mountain. A series of cones and black lava flows were passed in the northern part of the Uinkaret block, between the western scarps of the Shinarump mesa and the Hurricane ledge. The lava-floored valley above Workman spring has already been mentioned. The canyon of the Virgin just after the river emerges from the Hurricane ledge is cut in lava for several miles. A side canyon, about two miles south of Toquerville, revealed a fine section of a lava flow lying on a coarse gravel which partly filled a small valley, all shown in a single section. These latter items, along with many others, would be included in the special study of the Toquerville district, which may be so highly commended as a subject for a summer's field work.

Summary.

A high degree of consistence among the consequences of various associated theories is justly regarded as strong proof of the correctness of the theories themselves. Each of the earlier students of the Grand canyon district probably reviewed his conclusions to see that they were mutually consistent, and published only those that survived this test. As the progress of exploration and the advance of earth-science furnished more and more items in the sequence of events that make up the history of the district, the interlacing of more and more elements seemed to give at once greater difficulty to the problem and greater certainty to its solution. Dutton in particular appeals this aspect of the method of proof, and truly the successive steps in his thesis are strongly enchained. Yet it now seems possible to arrange a new sequence for some of the events by which the present order of things has been produced: a sequence which differs from that announced by previous observers in several particulars, as presented in the concluding summary below, although still holding to the main outlines of the geological history of the region as presented in the several governmental reports. The question then arises, where shall the permanent truth be found among all these suggested possibilities? Further exploration, and more particularly detailed study of certain special problems, will in due time review all the explanations now offered and select the survivors from among them. The work of new observers is especially needed in the examination of certain structures, as in the neighborhood of Toquerville, and between Pipe spring and the Toroweap; and in the discussion of dates of certain past phenomena, such as flexing, faulting, and uplifting; and in the discovery of the origin of the drainage system and the character of the climate of past periods. Whether the conclusions here announced shall then stand or fall in whole or in part, it would be a great reward to the writer if they might afford later students of the region even a small share of the aid that he has derived from the earlier work of Newberry and of Powell, of Gilbert and of Dutton.

The results reached in the foregoing pages may be summarized as follows. There is some probability that the San Rafael swell, like the Waterpocket flexure, is of pre-Tertiary origin. The other deformations of the region, both flexures and faults, are almost exclusively of much earlier date than the canyon cycle, and they may have been formed relatively early in the erosional history of the district. The total denudation of the region thus far accomplished may be considered in two parts, of which the first — the great denudation — was far advanced before the general uplift by which the second — the erosion of the canyon and the stripping of weak strata from the plateaus — was introduced. But the great denudation was complicated by repeated movements, after each of which the processes of erosion may have reached an advanced stage before the occurrence of the next series of disturbances. It is only by an analysis of these repeated movements and revived erosions that the origin of the drainage system can be determined. As far as this analysis can be attempted at present for the Grand canyon district, the side streams seem to be of various origins, except that none of them appear to be antecedent. The Colorado itself may be in part antecedent to some of the many dislocations that the district has suffered, but it seems to be for the most part consequent on the displacements caused by faulting in the later part of the great denudation, and on the form that the surface had assumed at that time. The floor of the Toroweap valley is higher than the neighboring valley floors, because it is sheeted with heavy lava flows which have effectively withstood the intermittent erosive efforts of wet-weather floods. The past climate of the region cannot be safely determined; a change from a humid to an arid climate at the close of the Miocene does not appear to be demanded by the facts that have been appealed to in its support.

BIBLIOGRAPHY.

Campbell, M. R.

Drainage Modifications and their Interpretation. Journ. Geol. (Chicago), Vol. IV., 1896, pp. 567–581, 657–678, (571–581).

Campbell, M. R. and Mendenhall.

Geologic Section along the New and Kanawha Rivers in West Virginia. 17th Ann. Rep. U. S. Geol. Surv., Part II., pp. 479–511.

Davis, W. M.

a. Notes on the Colorado Canyon District. Amer. Journ. Sci., Vol. X., 1900, pp. 251–259.

b. The Freshwater Tertiary Formations of the Rocky Mountain Region. Proc. Amer. Acad., Vol. XXXV., 1900, pp. 345–373.

c. Glacial Erosion in France, Switzerland, and Norway. Proc. Boston Soc. Nat. Hist., Vol. XXIX., 1900, pp. 273–322.

d. Glacial Erosion in the Valley of the Ticino. Appalachia, Vol. IX., 1900, pp. 136–156.

Dutton, C. E.

a. Report on the Geology of the High Plateaus of Utah, with Atlas. U. S. Geog. and Geol. Surv. Rocky Mountain Region, Washington, 1880.

b. The Physical Geology of the Grand Cañon District. 2d Ann. Rep. U. S. Geol. Surv., 1882, pp. 49–166.

c. Tertiary History of the Grand Cañon District, with Atlas. Monogr. II., U. S. Geol. Surv., 1882.

Emmons, S. F.

a. U. S. Geological Exploration of the Fortieth Parallel. Vol. II., Descriptive Geology, Washington, 1877.

b. The Origin of Green River. Science, Vol. VI., 1897, pp. 19–21.

Fairbanks, H. W.

Notes on the Geology of Eastern California. Amer. Geol., Vol. XVII., 1896, pp. 63–74.

Frech, F.

Section in Congress Canyon opposite Point Sublime. Compte-rendu 5th Internat. Congress of Geologists. New York, 1894, pp. 476–481.

Gilbert, G. K.

a. Report on the Geology of Portions of Nevada, Utah, California, and Arizona, examined in the years 1871 and 1872. Engineer Dep't U. S. Army. Report upon Geog. and Geol. Expl. W. of 100th Merid. Vol. III., Washington, 1875. Part I. pp. 17–187.

b. The Colorado Plateaux Province as a Field for Geological Study. Amer. Journ. Sci., Vol. XII., 1876, 16–24, 85–103.

c. Report on the Geology of the Henry Mountains. Dep't of the Interior, U. S. Geog. and Geol. Survey Rocky Mountain Region, Washington, 1877.

d. Lake Bonneville. Monogr. I., U. S. Geol. Surv., Washington, 1890.

e. Flagstaff to Grand Canyon. Geol. Guide-book for an Excursion to the Rocky Mountains. Compte-rendu 5th Internat. Congr. of Geol. New York, 1894, pp. 472, 473.

Hayes, C. W.

Physiography of the Chattanooga District in Tennessee. 19th Ann. Rep. U. S. Geol. Surv., Part II., 1899, pp. 1–58, (58).

Hayes, C. W., and Campbell, M. R.

Gemorphology of the Southern Appalachians. Nat. Geogr. Mag., Vol. VI., 1894, pp. 63–126, (105–107).

Holmes, W. H.

The Drawings by which the Colorado Canyon is so finely illustrated in Dutton's Reports (*b. c.*), are from the pencil, pen, and brush of this artist-geologist.

Howell, E. E.

Report on the Geology of Portions of Utah, Nevada, Arizona, and New Mexico, examined in the years 1872 and 1873. Engineer Dep't U. S. Army, Rep. upon Geog. and Geol. Expl. W. of 100th Merid., Vol. III., Washington, 1875. Part III., pp. 227–301.

Ives, J. C.

Report upon the Colorado River of the West. Senate, 36th Congress, 1st Session, in Washington, 1861, Part I. General Report, pp. 13–131.

Jefferson, M. S. W.

The Antecedent Colorado. Science, Vol. VI., 1897, pp. 293–295.

Jukes, J. B.

On the Mode of Formation of Some of the River Valleys in the South of Ireland. Quart. Journ. Geol. Soc., Vol. XVIII., 1862, pp. 378–403.

King, C.

U. S. Geological Exploration of the Fortieth Parallel. Vol. I. Systematic Geology. Washington, 1878.

McGee, W. J.

a. On the Origin and Hade of Normal Faults. Amer. Journ. Sci., Vol. XXVI., 1883, pp. 294–298.

b. Sheetflood Erosion. Bull. Geol. Soc. Amer., Vol. VIII., 1897, pp. 87–112.

c. Papagueria. Nat. Geogr. Mag., Vol. IX., 1898, pp. 345–371.

Marvine, A. R.

Report on the Geology of Route from St. George, Utah, to Gila River, Arizona. Engineer Dep't U. S. Army, Rep. upon Geog. and Geol. Expl. W. of 100th Merid., Vol. III., Washington, 1875, Part II., pp. 189–225.

Merriam, C. H.

Results of a Biological Survey of the San Francisco Mountain Region and Desert of the Little Colorado, Arizona. N. Amer. Fauna, No. 3, U. S. Dep't of Agriculture, Washington, 1890.

Newberry, J. S.

Report upon the Colorado River of the West. Senate, 36th Congr., 1st Session. Washington, 1861. Part III., Geological Report, pp. 1–154.

Penck, A.

Studien über das Klima Spaniens während der jüngeren Tertiär-periode und der Diluvialperiode. Zft. Ges. Erdk. Berlin, Vol. XXIX., 1894, pp. 109–141.

Philippson, A.

Das russische Flachland. Zft. Ges. Erdk. Berlin, Vol. XXXIII., 1898, pp. 37–68.

Powell, J. W.

a. Exploration of the Colorado River of the West and its Tributaries, explored in 1869, 1870, 1871, and 1372, under the Direction of the Secretary of the Smithsonian Institution. Washington, 1875.

b. Report on the Geology of the Eastern Portion of the Uinta Mountains and a region of country adjacent thereto, with Atlas. Dep't of the Interior. U. S. Geol. and Geog. Survey of the Territories. Washington, 1876.

c. Canyons of the Colorado. Meadville, Pa., 1895. (A general account of the Colorado River region, with reprint of certain portions of the original report and with the addition of many illustrations from various geological reports.)

d. The Cañons of the Colorado. Scribner's Monthly, Vol. IX., 1875, pp. 293–310, 394–409, 523–537.

Russell, I. C.

a. A Geological Reconnaissance in Southern Oregon. U. S. Geol. Surv. 4th Ann. Rep., Washington, 1884, pp. 431–464.

b. A Reconnaissance in Central Washington. Bull. No. 108, U. S. Geol. Surv., 1893.

Walcott, C. D.

a. Pre-Carboniferous Strata in the Grand Cañon of the Colorado, Arizona. Amer. Journ. Sci., Vol. XXVI., 1883, pp. 437–442, 484.

b. The Fauna of the Lower Cambrian or Olenellus Zone. 10th Ann. Rep. U. S. Geol. Surv., 1890, pp. 509–760.

c. The North American Continent during Cambrian Time. 12th Ann. Rep. U. S. Geol. Surv., 1891, pp. 523–568.

d. Study of a Line of Displacement in the Grand Cañon of the Colorado, in Northern Arizona. Bull. Geol. Soc. Amer., Vol. I., 1890, pp. 49–64.

e. Pre-Cambrian Igneous Rocks of the Unkar Terrane, Grand Canyon of the Colorado, Arizona. 14th Ann. Rep. U. S. Geol. Surv., 1894, pp. 497–519.

Wheeler, G. M.

Itinerary of Colorado Grand Canyon and River Trip of 1871, with Map. Engineer Dep't U. S. Army, Rep. upon Geog. Surveys W. of 100th Merid. Vol. I. Geog. Report, Washington, 1889, Chap. II., pp. 147–171. (A brief account of all previous explorations of the Colorado River is here included.)

EXPLANATION OF PLATES.

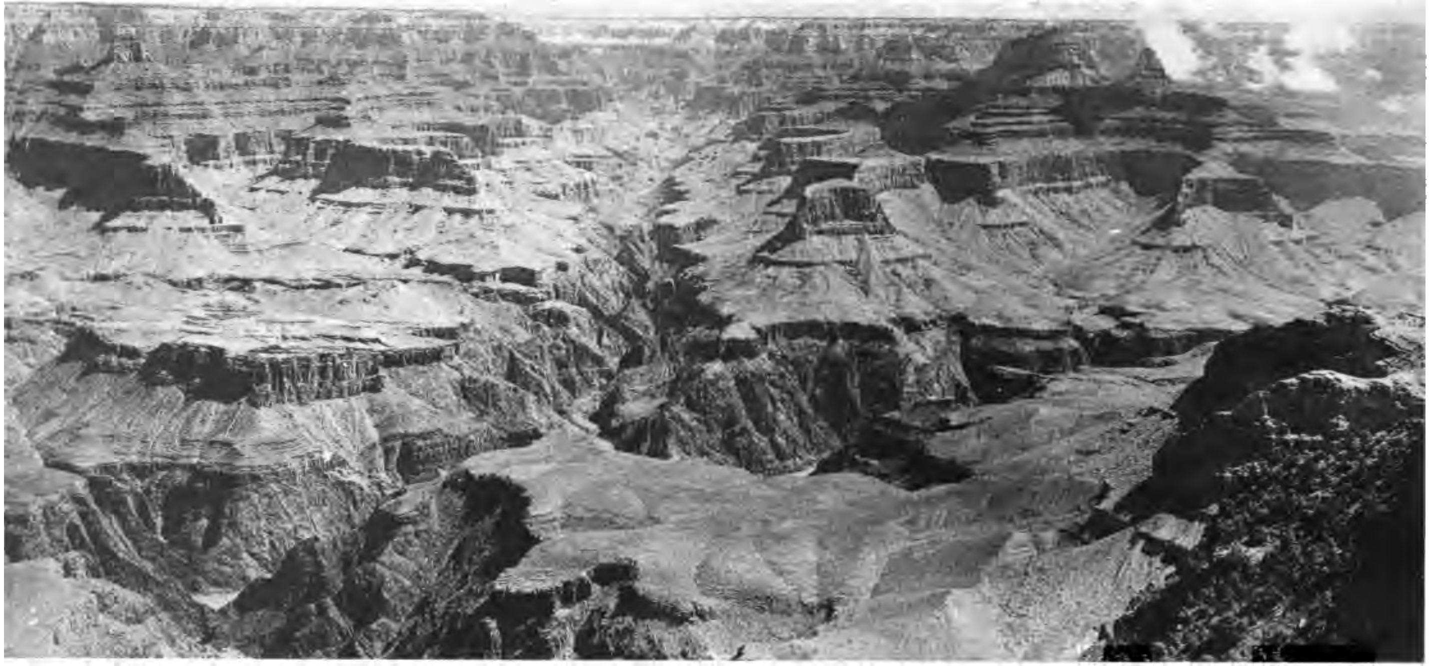
PLATE 1.

General view of the Colorado Canyon, looking about north from O'Neill's point to the Kaibab plateau. Copyright photograph by Detroit Photographic Co.

PLATE 2.

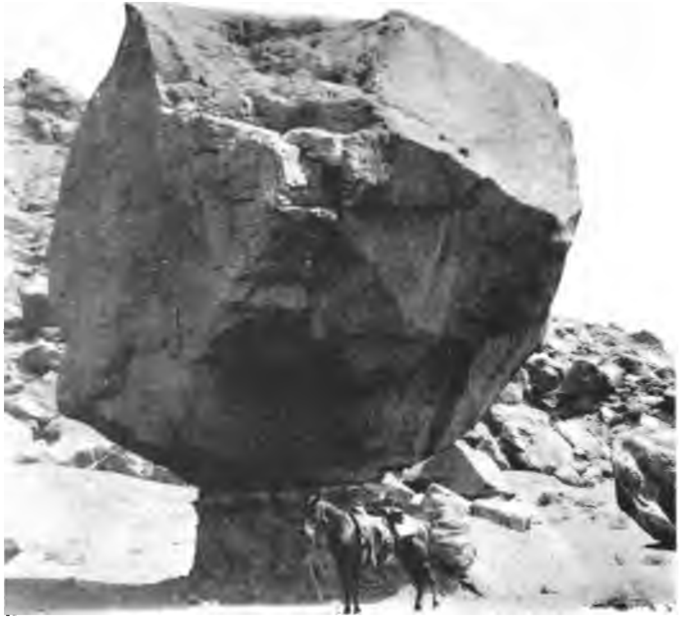
A. A shallow valley floor in the Coconino forest, south of the Colorado canyon; a hill and drying-ground of the farmer ant in the foreground. Photograph by Dr. H. E. Gregory.

B. A boulder of Shinarump sandstone perched on a pedestal of weak Permian shales at the base of the Shinarump bench, beneath Vermilion cliffs, Paria plateau, southwest of Lee's Ferry. Photograph by Dr. H. E. Gregory.



Copyright, 1900, Detroit Photographic Co.

GRAND CANYON OF THE COLORADO, LOOKING NORTH TO THE KAIBAB FROM O'NEILL'S POINT.



PERCHED BLOCK OF SHINARUMP SANDSTONE
AT BASE OF THE VERMILION CLIFFS.

Photo. by H. W. Gregory.

OPEN VALLEY ON THE COCONINO PLATEAU.

The following Publications of the Museum of Comparative Zoölogy are in preparation: —

Reports on the Results of Dredging Operations in 1877, 1878, 1879, and 1880, in charge of ALEXANDER AGASSIZ, by the U. S. Coast Survey Steamer "Blake," as follows: —

E. EHLERS. The Annelids of the "Blake."
C. HARTLAUB. The Comatulæ of the "Blake," with 15 Plates.
H. LUDWIG. The Genus Pentacrinus.
A. MILNE EDWARDS and E. L. BOUVIER. The Crustacea of the "Blake."
A. E. VERRILL. The Alcyonaria of the "Blake."

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of ALEXANDER AGASSIZ, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

Illustrations of North American MARINE INVERTEBRATES, from Drawings by BURKHARDT, SONREL, and A. AGASSIZ, prepared under the direction of L. AGASSIZ.

LOUIS CABOT. Immature State of the Odonata, Part IV.
E. L. MARK. Studies on Lepidosteus, continued.
" On Arachnactis.
R. T. HILL. On the Geology of the Windward Islands.
W. McM. WOODWORTH. On the Bololo or Palolo of Fiji and Samoa.
A. AGASSIZ and A. G. MAYER. The Acalephs of the East Coast of the United States.
AGASSIZ and WHITMAN. Pelagic Fishes. Part II., with 14 Plates.
J. C. BRANNER. The Coral Reefs of Brazil.

Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieutenant Commander Z. L. TANNER, U. S. N., Commanding, in charge of ALEXANDER AGASSIZ, as follows: —

A. AGASSIZ. The Pelagic Fauna.
" The Echini.
" The Panamic Deep-Sea Fauna.
K. BRANDT. The Sagittæ.
" The Thalassicolæ.
C. CHUN. The Siphonophores.
" The Eyes of Deep-Sea Crustacea.
W. H. DALL. The Mollusks.
H. J. HANSEN. The Cirripeds.
W. A. HERDMAN. The Ascidians.
S. J. HICKSON. The Antipathids.
W. E. HOYLE. The Cephalopods.
G. VON KOCH. The Deep-Sea Corals.
C. A. KOFOID. Solenogaster.
R. VON LENDENFELD. The Phosphorescent Organs of Fishes.
H. LUDWIG. The Starfishes.
J. P. McMURRICH. The Actinarians.
E. L. MARK. Branchiocerianthus.
JOHN MURRAY. The Bottom Specimens.
P. SCHIEMENZ. The Pteropods and Heteropods.
THEO. STUDER. The Alcyonarians.
M. P. A. TRAÜTSTEDT. The Salpidæ and Doliolidæ.
E. P. VAN DUZEE. The Halobatidæ.
H. B. WARD. The Sipunculids.
H. V. WILSON. The Sponges.
W. McM. WOODWORTH. The Nemerteans.
" The Annelids.

PUBLICATIONS

OF THE

MUSEUM OF COMPARATIVE ZOÖLOGY

AT HARVARD COLLEGE.

There have been published of the BULLETINS Vols. I. to XXXV.; of the Memoirs, Vols. I. to XXIV.

Vols. XXXVI., XXXVII., and XXXVIII. of the BULLETIN, and Vols. XXV., XXVI., XXVII. of the MEMOIRS, are now in course of publication.

The BULLETIN and MEMOIRS are devoted to the publication of original work by the Professors and Assistants of the Museum, of investigations carried on by students and others in the different Laboratories of Natural History, and of work by specialists based upon the Museum Collections and Explorations.

The following publications are in preparation: —

Reports on the Results of Dredging Operations from 1877 to 1880, in charge of Alexander Agassiz, by the U. S. Coast Survey Steamer "Blake," Lieut. Commander C. D. Sigsbee, U. S. N., and Commander J. R. Bartlett, U. S. N., Commanding.

Reports on the Results of the Expedition of 1891 of the U. S. Fish Commission Steamer "Albatross," Lieut. Commander Z. L. Tanner, U. S. N., Commanding, in charge of Alexander Agassiz.

Reports on the Scientific Results of the Expedition to the Tropical Pacific, in charge of Alexander Agassiz, on the U. S. Fish Commission Steamer "Albatross," from August, 1899, to March, 1900, Commander Jefferson F. Moser, U. S. N., Commanding.

Contributions from the Zoölogical Laboratory, Professor E. L. Mark, Director.

Contributions from the Geological Laboratory, in charge of Professor N. S. Shaler.

Subscriptions for the publications of the Museum will be received on the following terms: —

For the BULLETIN, $4.00 per volume, payable in advance.
For the MEMOIRS, $8.00 " " "

These publications are issued in numbers at irregular intervals; one volume of the Bulletin (8vo) and half a volume of the Memoirs (4to) usually appear annually. Each number of the Bulletin and of the Memoirs is also sold separately. A price list of the publications of the Museum will be sent on application to the Librarian of the Museum of Comparative Zoölogy, Cambridge, Mass.

QE86.G7 D38 1901
An excursion to the Grand Canyon of
Kummel Library AFP0269
3 2044 032 809 600

DATE DUE
JAN 26 1990
MAY 27 '94
MR 07 '00

QE86.G7 D38 1901